Materials Reliability Program: Alloy 82/182 Pipe Butt Weld Safety Assessment for US PWR Plant Designs (MRP-113NP)

1007029-NP

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NON-PROPRIETARY INFORMATION

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PRODUCT DESCRIPTION

Background

From 1999-2003 there were several incidences involving primary water stress corrosion cracking (PWSCC) of Alloy 82/132/182 butt welds in PWR plants in the US and abroad. These events resulted in unplanned or extended outages with associated economic costs.

In October 2000, the V.C. Summer plant shut down for a normal refueling outage. During the plant walkdown to visually inspect for leakage, significant boric acid deposits were discovered in the vicinity of the reactor vessel Loop A outlet nozzle-to-pipe weld. The origin of the leak was found to be a small pinhole in the Alloy 82/182 weld between the low-alloy steel reactor vessel outlet nozzle and the stainless steel primary coolant pipe. A review of plant records showed that the unidentified leak rate had been nearly constant at 0.3 gpm from all sources, well below the plant Technical Specification limit of 1 gpm.

Ultrasonic inspections from outside of the pipe were inconclusive. Ultrasonic inspections from inside the pipe revealed a single flaw near the top of the pipe. Destructive examination confirmed inside surface initiated axial cracking confined to the Alloy 182 nozzle-to-pipe weld and Alloy 182 buttering and a short shallow circumferential crack in the Alloy 182 buttering which arrested at the low-alloy steel nozzle.

In 2003, a small leak was discovered from an Alloy 132 (similar to Alloy 182) butt weld on a pressurizer relief nozzle at Tsuruga 2. This leak was also from an axial crack in the butt weld between the low-alloy steel nozzle and the stainless steel pipe.

Axial cracks without associated leaks have been discovered in Alloy 82/182 butt welds at Ringhals 3 and 4, V.C. Summer, Tsuruga 2 and Three Mile Island -1 (TMI-1). The only circumferential crack reported to date was the short shallow crack in the Alloy 182 buttering at V.C. Summer.

Objective

The objective of this report is to provide a safety assessment for primary water stress corrosion cracking (PWSCC) of Alloy 82/182 primary coolant system pipe butt welds in PWR plants. This assessment includes a compilation of Alloy 82/182 pipe weld locations in the primary systems of the three domestic NSSS designs. This report, and the supporting technical reports referenced in Section 2.4, provide the technical basis for an inspection plan for Alloy 82/182 butt welds which is currently being developed by the MRP.

Approach

The report begins with a summary description of experience with PWSCC of Alloy 82/132/182 butt welds in PWR plant primary coolant system applications, a review of the locations of these welds and a review of inspection technology and results. This is followed by a description of the methodology used to assess the safety of these welds on a generic basis. The safety assessment includes review of crack orientations and sizes, welding residual stresses in the as-designed and repaired conditions, crack growth rates, limiting flaw sizes, the ability to detect leaks before reaching a critical flaw size, deterministic safety assessments and probabilistic safety assessments. The document draws on work documented in other MRP reports, in particular MRP-106, MRP-109, MRP-112, MRP-114 and MRP-116.

Results

The final safety assessment shows that there is a very low probability of pipe rupture as a result of PWSCC of Alloy 82/182 welds in primary system applications. The butt welds have been inspected nondestructively at intervals specified by Section XI of the ASME Code. Only a small number of welds have been found to contain axial cracks, only two welds worldwide have been found to have small leaks from axial cracks, and only one weld had a reported circumferential crack which was both short and shallow. None of these cases involved significant risk of failure due either to cracks reaching critical size or boric acid corrosion. Analyses show that there is a high probability that leakage will be detected prior to failure.

EPRI Perspective

As a consequence of the hot leg nozzle weld leak at V.C. Summer in October 2000, the industry, acting through the EPRI Materials Reliability Program, undertook development of an interim safety assessment to assure continued safe operation. This work was reported in MRP-44, Part 1. Significant work has been performed since issuing the interim safety assessment to quantify the probability of leaks and failure and thereby confirm that it is safe to continue operating the plants. This work will form the basis for recommended visual and nondestructive examinations that will ensure a low probability of leaks and extremely low probability of failure in the future. This report documents the final safety assessment for Alloy 82/182 pipe butt welds drawing on work by several organizations.

Keywords

Primary water stress corrosion cracking
PWSCC
Alloy 600
Alloy 82/182
RV nozzle
RCS piping
Butt welds

ABSTRACT

This safety assessment summarizes industry effort to develop an integrated technical response to the issue of primary water stress corrosion cracking (PWSCC) of Alloy 82/182 butt welds in PWR plant primary coolant system applications. The report builds on the work in the interim safety assessment submitted to the NRC in 2001 (MRP-44, Part 1). The report addresses the background regarding leakage from an Alloy 82/182 hot leg nozzle to primary coolant pipe butt weld at V.C. Summer; leakage from an Alloy 132 pressurizer relief nozzle butt weld at Tsuruga 2; axial cracks in Alloy 82/182 butt welds at Ringhals 3 & 4, V.C. Summer, Tsuruga 2, and TMI-1; a compilation of locations where Alloy 82/182 butt welds are used; the safety assessment methodology; and results of safety assessments for the most important locations. Supporting documents include assessments of crack growth rates in Alloy 82/182 materials; assessments of Alloy 82/182 butt welds in Westinghouse, Combustion Engineering, and Babcock & Wilcox designed plants; elastic-plastic stress analyses of typical butt welds including the effect of welding residual stresses and weld repairs; and analyses that demonstrate a low probability of leakage and an extremely low probability of core damage consistent with the requirements of Regulatory Guide 1.174.

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1 INTRODUCTION

Primary water stress corrosion cracking (PWSCC) has been detected in Alloy 82/132/182 butt welds in several PWR plants. Leaks have occurred from axial through-wall cracks at two butt welds: an Alloy 182 reactor vessel outlet nozzle to hot leg reactor coolant pipe weld at V.C. Summer in 2000 and a pressurizer relief nozzle weld at Tsuruga 2 in 2003. A short shallow circumferential crack was discovered on the inside surface of the leaking V.C. Summer weld. Part-depth axial cracks have been discovered on the inside surfaces of several other Alloy 182 butt welds including reactor vessel nozzle to reactor coolant piping welds at V.C. Summer, Ringhals 3 and Ringhals 4; pressurizer safety and relief nozzle welds at Tsuruga 2; a hot leg pressurizer surge line nozzle weld at TMI-1; and possibly a pressurizer surge nozzle weld at Tihange. While not in the butt welds proper, leaks have occurred from circumferential through-wall cracks in the heat affected zones of Alloy 600 base metal adjacent to Alloy 82/182 butt welds at Palisades and in the US Navy Advanced Test Reactor (ATR).

An interim safety assessment was issued by the MRP in April 2001 [1] to address the most important butt welds, i.e., large diameter butt welds at high operating temperatures. This report demonstrated that plants have adequate safety margin to continue operation and provided several recommendations to enhance the sensitivity of inspection and operations personnel regarding potential for cracks and leaks.

In June 2001, the NRC provided a review of the interim safety assessment concluding that it provided a basis for continued safe operation while additional analyses and inspections are performed [2]. In April 2003, the NRC indicated that the assumption that boric acid corrosion is not a concern due to low leak rates and high temperatures may have to be revisited in light of RPV head nozzle experience at Davis-Besse [3].

The purpose of this report is to provide the final safety assessment addressing PWSCC of Alloy 82/182 butt welds in PWR plant primary systems. This report provides an overview of the work performed and conclusions relative to the domestic PWR fleet. The complete safety assessment is comprised of this summary report and the supporting documents referenced in Section 2.4 that were prepared by NSSS vendors and MRP contractors.

2 BACKGROUND

The following is an overview of experience with PWSCC of Alloy 82/132/182 butt welds, the interim safety assessment, the NRC review of the interim safety assessment, and a roadmap to the documents that comprise the final safety assessment relative to Alloy 82/182 butt welds in US plants.

2.1 Cracks and Leaks in Alloy 82/132/182 Butt Welds

Over the period 1999-2003 there were several incidences involving primary water stress corrosion cracking (PWSCC) of Alloy 82/132/182 butt welds in PWR plants in the US and abroad. These events resulted in unplanned or extended outages with associated economic costs.

During the October 2000 refueling outage at V.C. Summer, boric acid crystal deposits were discovered in the vicinity of the reactor vessel Loop A outlet nozzle-to-pipe butt weld. Investigation showed that the boric acid had come from a small hole in the Alloy 82/182 butt weld between the low-alloy steel reactor vessel outlet nozzle and the stainless steel primary coolant pipe [4,5,6,7,8]. While the exact leak rate from the weld flaw is not known, a review of plant leakage records showed that the unidentified leakage rate had been nearly constant at 0.3 gpm from all sources, well below the plant Technical Specification limit of 1 gpm. Ultrasonic inspections from the pipe outside surface were inconclusive. Ultrasonic examinations from inside the pipe revealed a single axial flaw in the butt weld near the top of the pipe. Destructive examination showed 1) a through-wall axial crack extending essentially the full weld width, 2) several other part-depth axial cracks in the weld, and 3) a short shallow circumferential crack in the Alloy 182 cladding that arrested when it reached the low-alloy steel nozzle. The main axial and circumferential flaws are indicated in Figure 2-1.a. The root cause assessment showed that the butt weld had been extensively repaired, including repairs made from the inside surface. Stress analyses [9] confirmed the detrimental effect of weld repairs made from the inside surface. Nondestructive examinations of other V.C. Summer reactor vessel outlet and inlet nozzles showed several shallow axial indications.

During inservice inspections of Ringhals 3 in 1999 [10] and Ringhals 4 in 2000 [10,11,12,13], part-depth axial flaws were found in Alloy 182 reactor vessel outlet nozzle to hot leg safe end butt welds. In the case of Ringhals 3 the flaws were evaluated and left in service. In the case of Ringhals 4, the flaws were removed by taking contoured boat samples without making weld repairs. The Ringhals nozzles differ from RPV nozzles in the United States in that they have double-V as opposed to single-V welds (see Figure 2-1.b).

In October 2002, an axial indication was discovered in a pressurizer surge line nozzle to safe-end butt weld at Tihange 2 [14]. The indication, which was located close to a fabrication repair, was left in place and reinspected in May 2003. It was reported that the reinspection showed no growth. Based on the lack of observed crack growth, it is possible that the indication may not be PWSCC.

In September 2003 a small leak was discovered from a pressurizer relief nozzle butt weld at Tsuruga 2 [15,16]. The leak was determined to be from an axial crack through the Alloy 132 butt weld that terminated at the low-alloy steel nozzle and the stainless steel pipe. As shown in Figure 2-2, the cross section of the axial crack was similar in extent to the through-wall crack at V. C. Summer in that it arrested at the low-alloy steel nozzle and stainless steel pipe. The butt weld at Tsuruga 2 that developed the leak had been repaired from the outside surface. Inspections showed a second, nearly through-wall, crack in the same nozzle at Tsuruga 2, and axial indications in a safety nozzle weld.

During the fall of 2003 a part depth (approximately 45% through wall) axial indication was discovered in a repaired hot leg pressurizer surge line nozzle butt weld at TMI-1. The indication had the characteristics of PWSCC, but the presence of PWSCC was not confirmed. The nozzle was repaired by applying a structural weld overlay [16].

In addition to the experience summarized above involving predominantly axial cracks, there have been two cases involving significant size through-wall circumferential cracks in the heat affected zone of Alloy 600 base material adjacent to an Alloy 182 butt weld.

- In 1993, a pressurizer PORV nozzle safe end at Palisades was discovered to have a leak resulting from a through-wall crack in the Alloy 600 safe end base metal about 0.08" from the NiCrFe field weld (see Figure 2-3). This crack was not in the Alloy 182 weld proper but is included for information purposes since it was adjacent to the weld [4].
- A leak was discovered in the heat affected zone of an Alloy 600 elbow welded to an Alloy 600 nozzle on the US Navy Advanced Test Reactor (ATR) [17]. The elbow (shown in Figure 2-4) was 1-1/2 inch Schedule 80 that operated in stagnant steam at 620°F and 1,800 psi. The leak developed after approximately 20 years of service. The leak was traced to a through-wall circumferential flaw that initiated at a burn-through location that occurred when making the initial pass. The flaw propagated through the grain growth portion of the heat affected zone to the outside surface. The crack length was approximately 0.5 inch on the inside surface and the leak exited at a large pit (0.04 inch diameter) on the outside surface. SEM examinations showed microcracks of up to 0.0015 inch depth at the underbead edge. The cracks did not propagate into the weld metal proper. In fact, it was reported that shallow penetrations into the weld metal had blunt tips suggesting that they had existed for a long time without propagation. The elbow inside surface was reported as being rough and containing gouges probably related to the forming process. The elbow base metal exhibited a lack of grain boundary carbide decoration. The root cause analysis identified the base metal microstructure, the weld underbead geometry and the possible presence of high welding residual stresses as contributing factors.

Despite the small numbers of cracks and leaks described above, the overall industry experience with Alloy 82/182 butt welds has been generally good. Specifically, all of the 1150+ Alloy 82/182 butt welds greater than 1" NPS in domestic PWR plants require visual examinations and approximately 930 Alloy 82/182 pipe butt welds 4" NPS and greater have been volumetrically examined at 10 year intervals per requirements of Section XI of the ASME Boiler and Pressure Vessel Code. The inspections in domestic plants have shown a small number of part-depth axial cracks, one weld with a leak, and one weld with a short shallow circumferential crack. Experience in other countries has been similar with a few welds containing part depth axial cracks limited to the width of the welds and one plant (Tsuruga 2) with a small leak at an axial crack. The leaks have been detected by visual inspections, the leak rates have been low enough that they have not resulted in any significant amount of boric acid corrosion, and the cracks have been predominantly axial and limited to the width of the butt weld such that they pose a low probability of rupture. With the exception of welds to Alloy 600 pipe or Alloy 600 safe ends, axial cracks in the weld metal do not propagate beyond the width of the weld since the adjoining low-alloy steel nozzles and stainless steel pipes are not susceptible to PWSCC. Cracks can extend into these materials by fatigue, but the rate of fatigue crack growth is slow.

The above experience suggests that primary attention should be directed towards locations where there are Alloy 82/182 butt welds to Alloy 600 nozzles or safe ends. These locations have the demonstrated potential for through-wall circumferential cracks in the base metal heat affected zone (Palisades and ATR). These locations also have the potential for axial cracks that initiate in the welds to propagate into the Alloy 600 base metal resulting in through-wall axial cracks longer than the width of the butt weld. Locations meeting these criteria occur at welds to CRDM/CEDM/ICI nozzles, some bottom head instrument nozzles, small diameter instrument nozzles in many plants, and pressurizer spray and relief nozzle safe ends in some plants. Most of these applications are less than 1" NPS and some, which are located outboard of the pressure boundary and/or outside of the insulation, operate at temperatures below the cold leg temperature. Larger size Alloy 600 safe ends are limited to a few locations described in paragraph 3.4. However, at these locations the crack growth rates in the Alloy 600 base metal are expected to be lower than in the weld metal and the combined axial lengths of the Alloy 82/182 butt welds and Alloy 600 safe ends may be less than the critical axial lengths.

2.2 Interim Safety Assessment

In response to the flaws in butt welds at V.C. Summer and Ringhals 3 and 4, the MRP prepared report TP-1001491, Part 1, PWR Materials Reliability Project – Interim Alloy 600 Safety Assessments for US PWR Plants (MRP-44) – Part 1: Alloy 82/182 Pipe Butt Welds [1]. This report was submitted to the NRC in April 2001. This report addressed the most important butt welds (largest diameter and highest temperature) in each type of plant. The main conclusions from this report were as follows:

a. As of April 2001, there had not been a history of widespread problems with PWSCC of Alloy 82/182 pipe butt welds.

   – While bare metal visual inspections had identified a number of leaks in Alloy 600 parts (CRDM nozzles, small diameter instrument nozzles, pressurizer heater sleeves, etc.) only one leak (V.C. Summer) had been discovered in an Alloy 82/182 butt weld at the time the interim report was issued. There was significant margin over required safety margins at the time this leak was discovered.

- All plants in the US inspect Alloy 82/182 butt welds in RCS pipes 4 inch NPS and greater at 10-year intervals as specified by Section XI of the ASME Code. While experience at V.C. Summer demonstrated the need for improvements to the NDE technology, the absence of findings from these inspections suggested that the number of welds with cracks was low.

b. Field experience and finite element analysis of welding residual and operating stresses demonstrated that if cracks develop in the welds, they are likely to be axially oriented.

c. Axial crack lengths in pipe butt welds bounded by low-alloy steel or stainless steel at either end of the weld are limited to the widths of the weld. The critical flaw size for rupture is much greater than the axial width of the butt welds.

d. Through-wall part-circumferential cracks will produce leaks that can be detected before compromising structural integrity.

e. Part-depth 360° circumferential flaws are not expected to occur in PWR butt welds.

f. There is significant defense-in-depth for components with cracks in Alloy 82/182 weld metal at the locations of interest. First, analyses demonstrate that these cracks do not significantly increase the core damage frequency (CDF). Second, postulated instantaneous double-ended primary coolant pipe breaks are analyzed accidents per the FSAR.

g. There is no concern with boric acid corrosion as a result of the relatively low leak rates from the tight PWSCC cracks and the high temperatures of the components.

2.3 NRC Review Comments Regarding Interim Safety Assessment

By a letter dated June 14, 2001 [2], the NRC provided comments on report MRP-44, Part 1. The NRC findings are summarized in Appendix A.

By letter dated April 22, 2003 to NEI [3], the NRC indicated that PWSCC of Alloy 82/182 butt welds is still a concern and that it is important to finalize the safety assessment. This letter stated that the assumption in the Part 1 report, that there is no concern with boric acid corrosion as a result of the relatively low leak rates and high component temperatures, has been proven to be invalid.

The MRP has performed work to strengthen the safety assessment and to address the NRC concerns. The work is summarized in this integrated safety assessment report. Appendix A to this document provides a summary of the responses to each of the NRC comments.

2.4 Roadmap to Final Safety Assessment Documents

As stated in the introduction, this report provides an overview of the work performed and the conclusions relative to the domestic PWR fleet. The complete final safety assessment is comprised of this summary report and seven supporting documents prepared by NSSS vendors and other MRP contractors. Figure 2-5 is a roadmap to the detailed documents that support this summary safety assessment. These documents are as follows:

a. Evaluation of Crack Growth Rates in Alloy 82/182 Weld Metal
Based on the relevant worldwide laboratory data, the MRP has developed deterministic crack growth rate models for Alloy 600 base metal and Alloy 82/182 weld metal. EPRI convened an international panel of experts to provide detailed technical input to the process used to develop these models. The work on Alloy 600 base metal has been completed and is documented in report MRP-55 [18]. The MRP has completed its technical assessment of crack growth rates in Alloy 82/182 weld metal and has issued findings in the minutes of an October 3, 2003, panel meeting [19]. A final MRP report fully documenting this work will be issued later in 2004.

b. Assessment of Crack Orientations and Lengths in BWR Butt Welds
General Electric was tasked by EPRI-MRP to review the orientations and sizes of axial and circumferential cracks in boiling water reactor (BWR) pipe butt welds. The purpose of this effort was to support the technical case that part-depth 360° circumferential cracks are unlikely to occur in service. The results of this review are documented in an MRP report (MRP-57) [20].

c. Deterministic Safety Assessment for Alloy 82/182 Butt Welds in Westinghouse and CE Plants
Westinghouse was tasked by the EPRI-MRP to perform deterministic analyses to assess butt weld PWSCC in Westinghouse and Combustion Engineering design plants. The final report of this work describes the most likely flaw orientations, calculates allowable flaw sizes, predicts crack growth rates, and provides an assessment of leakage detectability prior to risk of rupture [21]. This report, MRP-109 was prepared using an early crack growth rate equation [22] for Alloy 182 weld metal. Report MRP-109 was updated by a letter report [23] to evaluate the effect of the final crack growth rate model developed by the MRP [19].

d. Deterministic Safety Assessment for Alloy 82/182 Butt Welds in Babcock & Wilcox Plants
AREVA was tasked by the EPRI-MRP to perform deterministic analyses to assess butt weld PWSCC in Babcock & Wilcox design plants. The final report of this work describes the most likely flaw orientations, calculates allowable flaw sizes, predicts crack growth rates, and provides an assessment of leakage detectability prior to risk of rupture [24]. This report (MRP-112) was prepared using an early crack growth rate equation [22] for Alloy 182 weld metal. Report MRP-112 was also updated by a letter report [25] to evaluate the effect of the final crack growth rate model developed by the MRP [19].

e. Welding Residual and Operating Stresses in Alloy 182 Butt Welds
The previously noted Westinghouse and AREVA safety assessments were performed using generic welding residual stresses for thinner wall austenitic stainless steel pipe butt welds similar to those in BWR plants. Dominion Engineering, Inc. performed analyses (MRP-106) to determine welding residual stresses for Alloy 182 butt welds in PWR plant applications ranging from 30" diameter reactor vessel outlet nozzle to primary coolant piping butt welds to 1" diameter instrument nozzle butt welds [26]. The work also includes assessment of 360° and part-circumferential weld repairs to the inside surfaces of larger size welds where there is

access to the inside surface, and assessment of the potential benefit of weld overlay deposits in reducing inside surface tensile stresses. This work serves as input to the fracture mechanics assessment of weld repairs in paragraph 6.4.

f. Fracture Mechanics Assessment Including Effect of Weld Repairs
Structural Integrity Associates, was tasked by the EPRI-MRP to assess the effect of 360° and part-circumferential weld repairs on the geometry of potential circumferential cracks and on the extent of through-wall and circumferential crack growth [27]. This work (MRP-114) is based on the welding residual stresses determined from the analyses reported in paragraph 2.4.e. The document also includes a review of typical pipe/nozzle weld repairs and a summary of potentially applicable BWR experience.

g. Probabilistic Risk Assessment of Alloy 82/182 Butt Welds
The previous documents have involved deterministic type assessments. The final supporting document prepared by Westinghouse (MRP-116) [28] provides the results of probabilistic fracture mechanics analyses to assess the probability of leaks, the probability of rupture due to crack growth, and the change in core damage frequency (CDF) resulting from PWSCC of Alloy 82/182 butt welds. This work includes the effects of industry cracking statistics, crack orientations and lengths, and non-destructive examinations to detect cracks at an early stage. This work is used to confirm that there is a low probability of leakage and an extremely low predicted core damage frequency (CDF) consistent with requirements of Reg. Guide 1.174 [29].

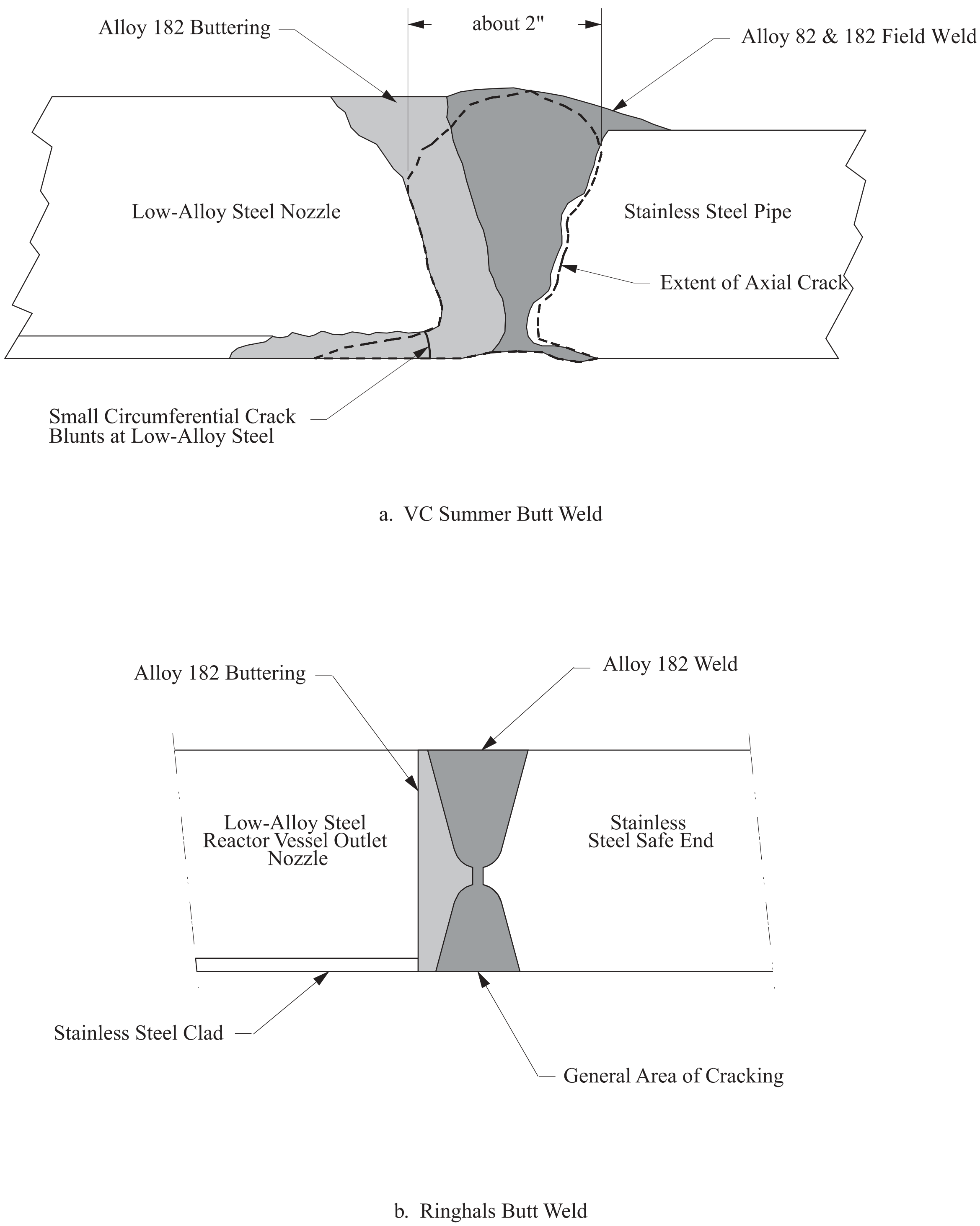
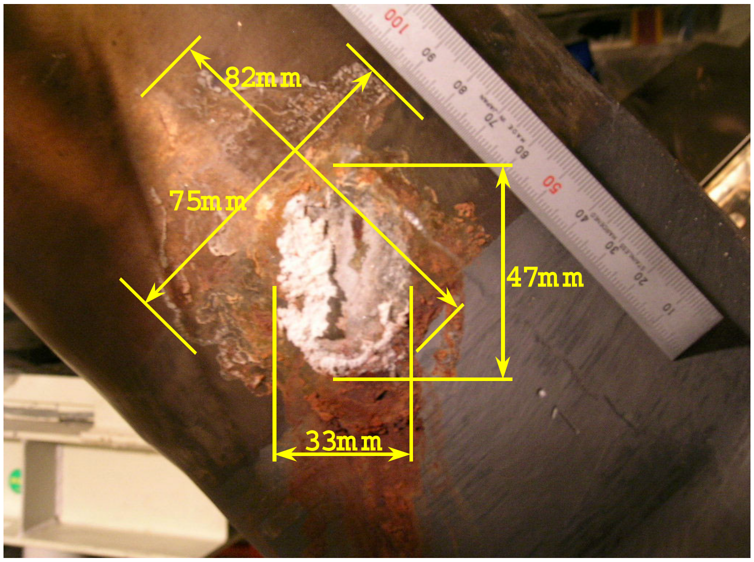
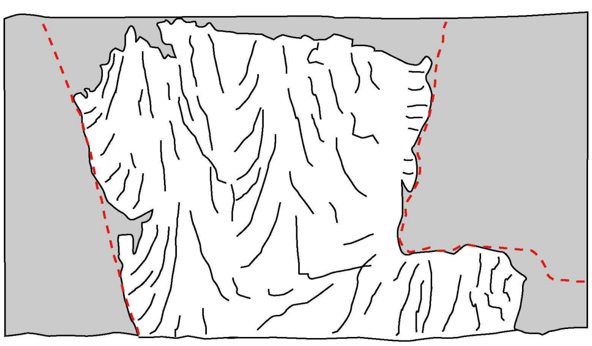


Figure 2-1
Cross Sections Through V.C. Summer and Ringhals Welds Showing Flaw Locations

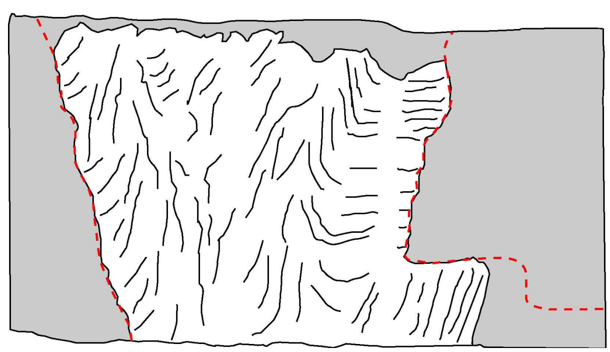


a. Photograph of Boric Acid at Leak

Note that while both cracks extend essentially the entire length of the weld and buttering, the crack only broke through to the surface at the 90° cross section.



b. Cross Section at Leak (90°)



c. Cross Section at Crack (315°)

Figure 2-2
Leak from Pressurizer Relief Nozzle Butt Weld at Tsuruga 2 [15]

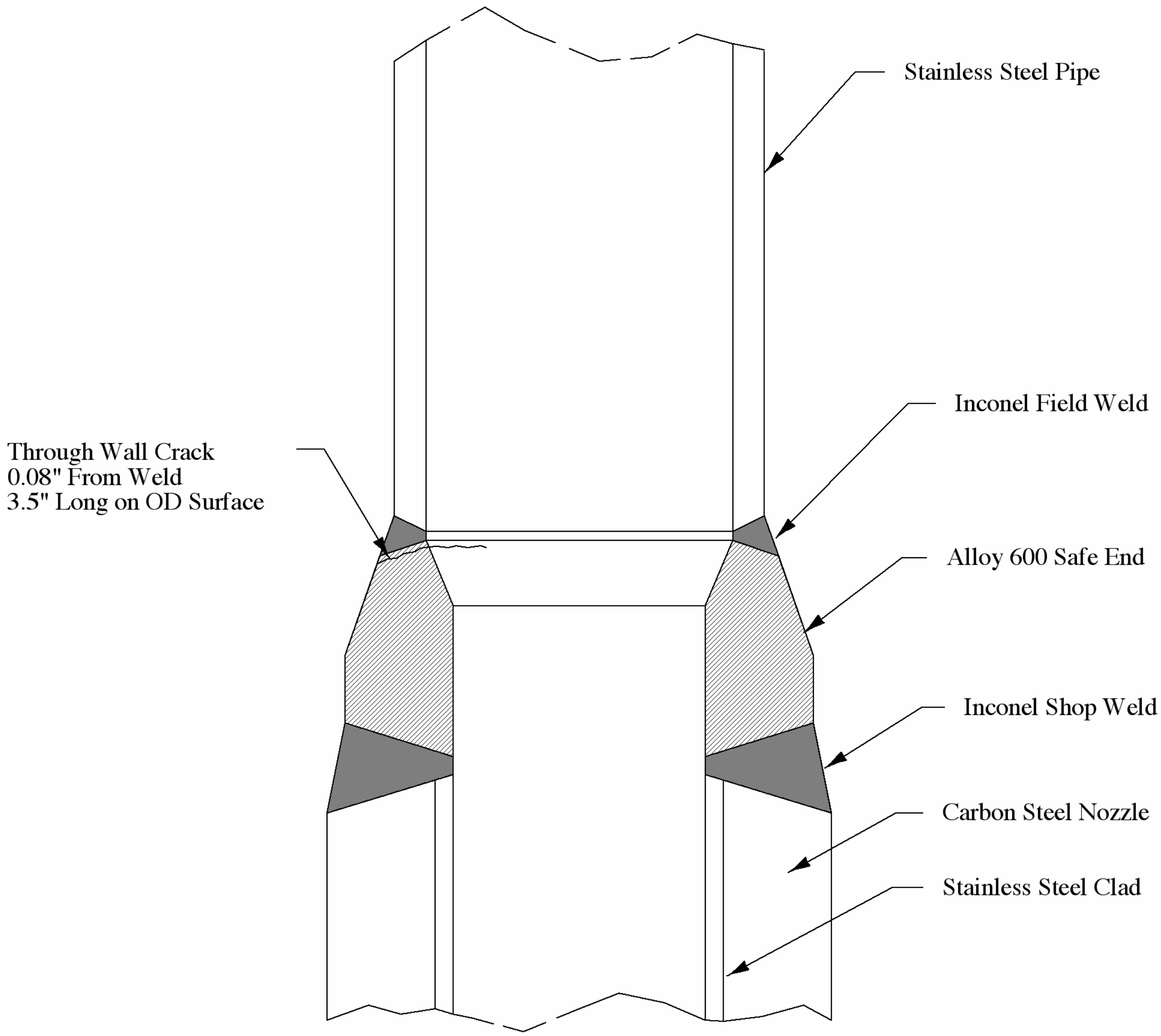


Figure 2-3
Circumferential Crack Adjacent to Alloy 182 Butt Weld on Palisades PORV Safe End [4]

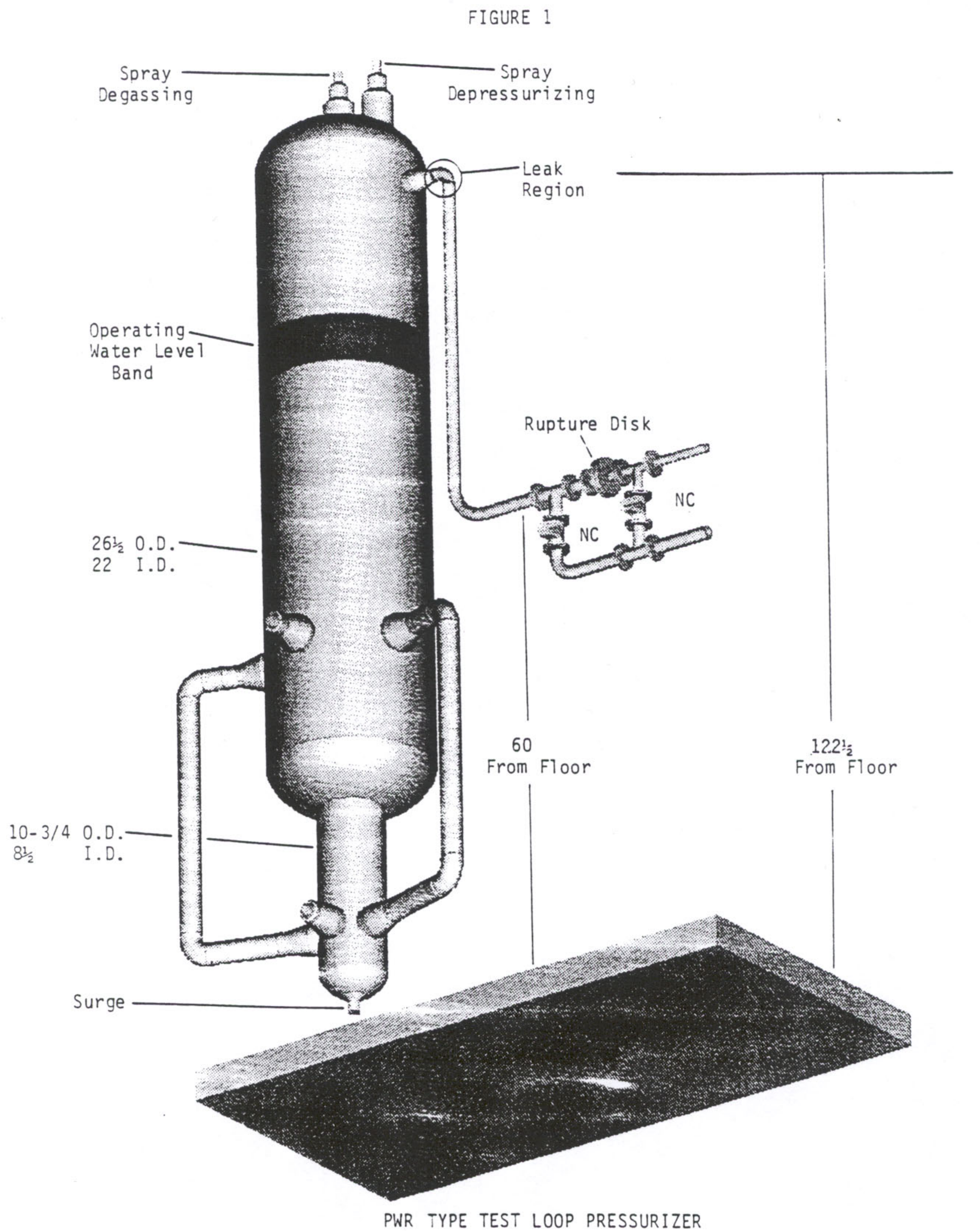


Figure 2-4
Elbow in US Navy Advanced Test Reactor (ATR) with Through-Wall Circumferential Crack in HAZ [17]

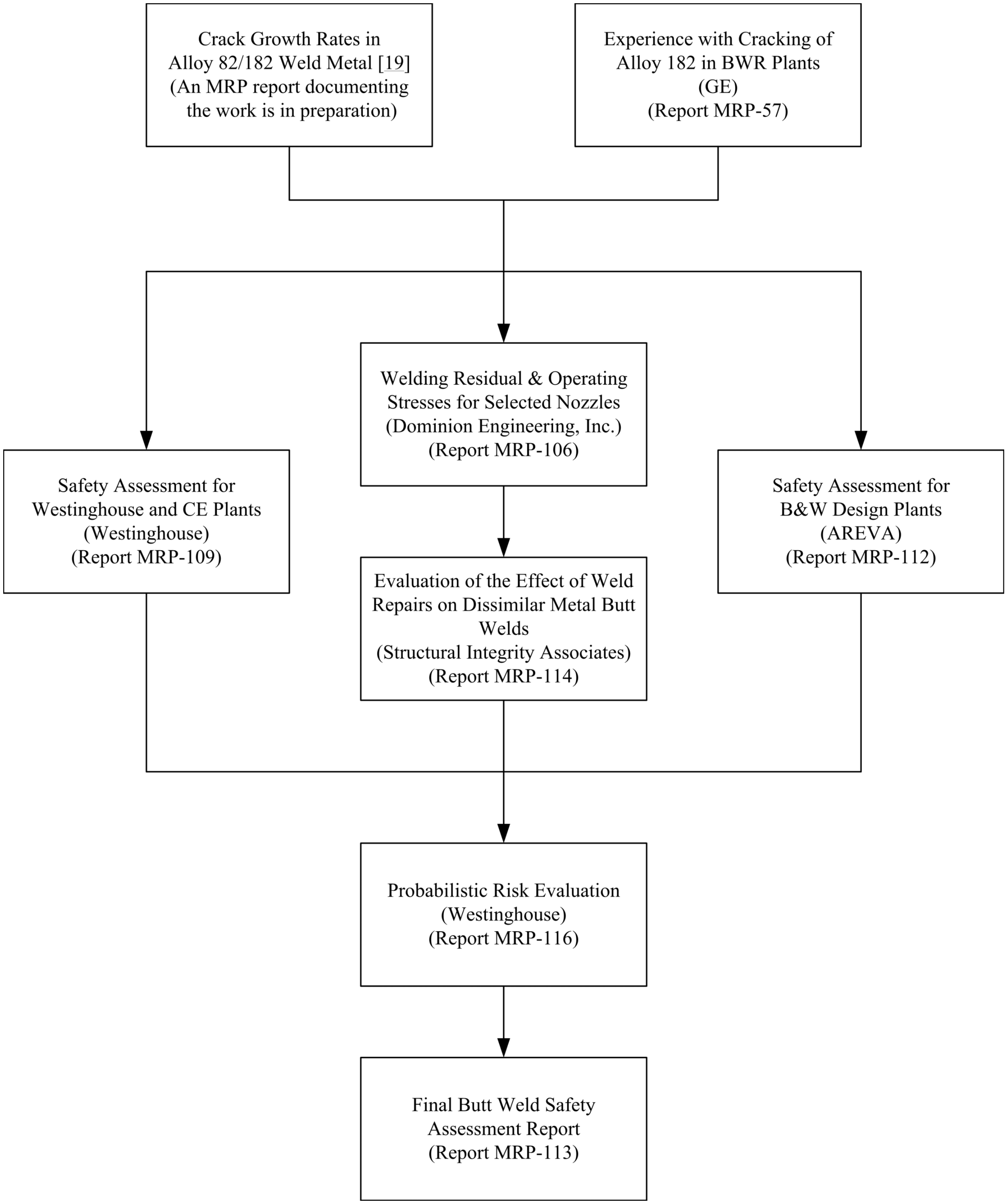


Figure 2-5
Roadmap to Documents Comprising Final Butt Weld Safety Assessment

3
PRIMARY SYSTEM LOCATIONS WITH ALLOY 82/182 PIPE BUTT WELDS

Important Alloy 82/182 butt welds in plants designed by Babcock & Wilcox, Combustion Engineering, and Westinghouse, based on size and operating temperature, are listed in Table 3-1. These are welds greater than 1 inch NPS in locations operating at 550°F and higher. These locations, and the range of key parameters for each type of weld, are shown in Figures 3-1 through 3-3 for the three NSSS designs. The table and figures do not include butt welds to instrument nozzles 1 inch NPS and less or butt welds in CRDM nozzles, RPV bottom head instrument nozzles and core flood tank components that operate at temperatures below 550°F. Paragraphs 3.1 through 3.3 provide further information regarding Alloy 82/182 butt welds for each of the three NSSS designs.

Based on this study, the most important locations were selected for further assessment as described in Sections 6 and 7.

3.1 Locations in Westinghouse Design Plants

Locations and details of Alloy 82/182 butt welds in Westinghouse design plants are provided in the Westinghouse safety assessment [21] and are summarized in Figure 3-1 for a typical 3 loop plant configuration. Westinghouse plants have stainless steel primary coolant piping. As a result, there are large diameter butt welds between the stainless steel piping and the low-alloy steel reactor vessels and steam generators. Most of the butt welds at reactor vessel outlet nozzles are single-V Alloy 82/182 welds. Butt welds between the reactor coolant piping and the steam generator nozzles were stainless steel except for one plant which has Alloy 82/182 butt welds at this location.

Since the primary coolant piping is stainless steel, most of the smaller diameter branches from the primary coolant pipes are also stainless steel, eliminating the need for Alloy 82/182 welds at the branch connections.

The only other Alloy 82/182 pipe butt welds greater than 1 inch NPS, and operating at cold leg temperature and above, are between the low-alloy steel pressurizer and the stainless steel surge, spray and safety/relief valve lines.

3.2 Locations in Combustion Engineering Design Plants

Locations and details of Alloy 82/182 butt welds in Combustion Engineering (CE) design plants are also provided in the Westinghouse safety assessment [21] and are summarized in Figure 3-2. The primary coolant piping in all but one of the CE design plants is low-alloy steel. Therefore, the only large diameter Alloy 82/182 butt welds are between the cold leg pipes and the stainless steel reactor coolant pump casing. Two exceptions are Fort Calhoun, which has stainless steel primary loop piping and is assessed with the Westinghouse plants, and Palo Verde which has low alloy steel reactor coolant pump casings.

Most branch lines to the low-alloy steel primary coolant piping are stainless steel and there are Alloy 82/182 butt welds at the connection nozzles. This leads to a large number of smaller diameter Alloy 82/182 butt welds at the hot leg and cold leg piping branch nozzles.

The only other Alloy 82/182 pipe butt welds greater than 1 inch NPS, and operating at cold leg temperature and above, are between the low-alloy steel pressurizer and the stainless steel surge, spray and safety/relief valve lines.

3.3 Locations in B&W Design Plants

Locations and details of Alloy 82/182 butt welds in Babcock & Wilcox (B&W) design plants are provided in the AREVA safety assessment [24] and are summarized in Figure 3-3. The primary coolant piping in B&W design plants is low-alloy or carbon steel. Therefore, the only large diameter Alloy 82/182 butt welds are between the cold leg pipes and the stainless steel reactor coolant pump casings.

The core flood lines are stainless steel and there are Alloy 82/182 butt welds where these lines enter the reactor vessel. This location operates between the hot and cold leg temperatures. There are Alloy 82/182 butt welds at the inlet to each of the two core flood tanks and at core flood tank pressure relief nozzles. However, these butt welds operate at essentially room temperature and are not considered further in the safety assessment.

Most branch lines to the low-alloy steel primary coolant piping are stainless steel and there are Alloy 82/182 butt welds at the connection nozzles. This leads to a large number of smaller diameter Alloy 82/182 butt welds at the hot leg and cold leg piping branch nozzles.

The only other Alloy 82/182 pipe butt welds greater than 1 inch NPS, and operating at cold leg temperature and above, are between the low-alloy steel pressurizer and the stainless steel surge, spray and safety/relief valve lines.

3.4 Locations with Alloy 600 Safe Ends or Pipe

As previously noted, there are two concerns at locations with Alloy 600 safe ends or pipe. First, experience at Palisades and the navy ATR has shown the potential for through-wall circumferential cracks in the heat affected zone of the Alloy 600 base metal. Second, if axial cracks develop in the Alloy 82/182 butt welds, the cracks can continue to propagate into the Alloy 600 base metal rather than arresting as would be the case for welds to low-alloy steel nozzles. A survey of plant designs shows that the only locations with Alloy 82/182 butt welds to Alloy 600 safe ends in sizes greater than 1 inch NPS, and which operate at 550°F and greater, are the pressurizer spray nozzles in B&W design plants and several nozzles at Palisades. At the pressurizer spray nozzle safe ends in B&W design plants the critical length of through-wall axial flaws is greater than the combined length of the Alloy 82/182 butt welds and the Alloy 600 safe end such that there is no risk of rupture.

Table 3-1
Typical Locations Involving Alloy 82/182 Pipe Butt Welds[1]

Location	Westinghouse Design Plants	Combustion Engineering Design Plants	Babcock & Wilcox Design Plants
Reactor Vessels			
- Inlet & Outlet Nozzles	Yes	No[2]	No
- Core Flood Nozzles	No	No	Yes
Pressurizers			
- Surge Line Nozzles	Yes	Yes	Yes
- Spray Nozzles	Yes	Yes	Yes
- Safety & Relief Valve Nozzles	Yes	Yes	Yes
RCS Piping Loop			
- SG Inlet & Outlet Nozzles	No[4]	No	No
- RCP Suction & Discharge Nozzles	No	Yes[3]	Yes
RCS Branch Line Connections			
- HL Pipe to Surge Line Connection	No	Yes	Yes
- Charging Inlet Nozzles	No	Yes	Yes
- Safety Injection and SDC Inlet	No	Yes	Yes
- Shutdown Cooling Outlet Nozzle	No	Yes	Yes
- Pressurizer Spray Nozzles	No	Yes	Yes
- Let-Down and Drain Nozzles	No	Yes	Yes

1. Table does not include butt welds in instrument nozzles 1 inch NPS and smaller, or welds that operate at less than 550°F (CRDM nozzle to flange butt welds, BMI nozzle to pipe butt welds, core flood tank nozzle butt welds).
2. One CE design plant has Alloy 82/182 welds and is evaluated with the Westinghouse design plants.
3. Palo Verde does not have Alloy 82/182 RCP suction and discharge nozzle welds.
4. One plant has Alloy 82/182 butt welds at this location.

Application	Identification Number in Figure 3-1	Typical Temperature (°F)	Typical ID (inches)	Typ. Number (3 Loop Plant)
Pressurizer - Surge Line Nozzle - Spray Nozzle - Safety/Relief Nozzles	 1 2 3	653	 10 4 5	 1 1 4
RCS Hot Leg Pipe - Reactor Vessel Outlet Nozzles[3] - Steam Generator Inlet Nozzles[4]	 4 5	600-620	 29 --	 3 --
RCS Cold Leg Pipe - Steam Generator Outlet Nozzles[4] - Reactor Vessel Inlet Nozzles[3]	 6 7	550-560	 -- 27.5	 -- 3

1. Figures only show locations in pipes greater than 1" NPS and operating at temperatures greater than about 550°F.
2. Plants with original reactor vessel closure heads have CRDM nozzles with Alloy 82/182 nozzle-to-flange butt welds (4" diameter).
3. There are no Alloy 82/182 RPV nozzle welds in Westinghouse 2-loop plants and some early Westinghouse 3-loop plants.
4. One plant has Alloy 82/182 butt welds between the reactor coolant piping and steam generator nozzles.

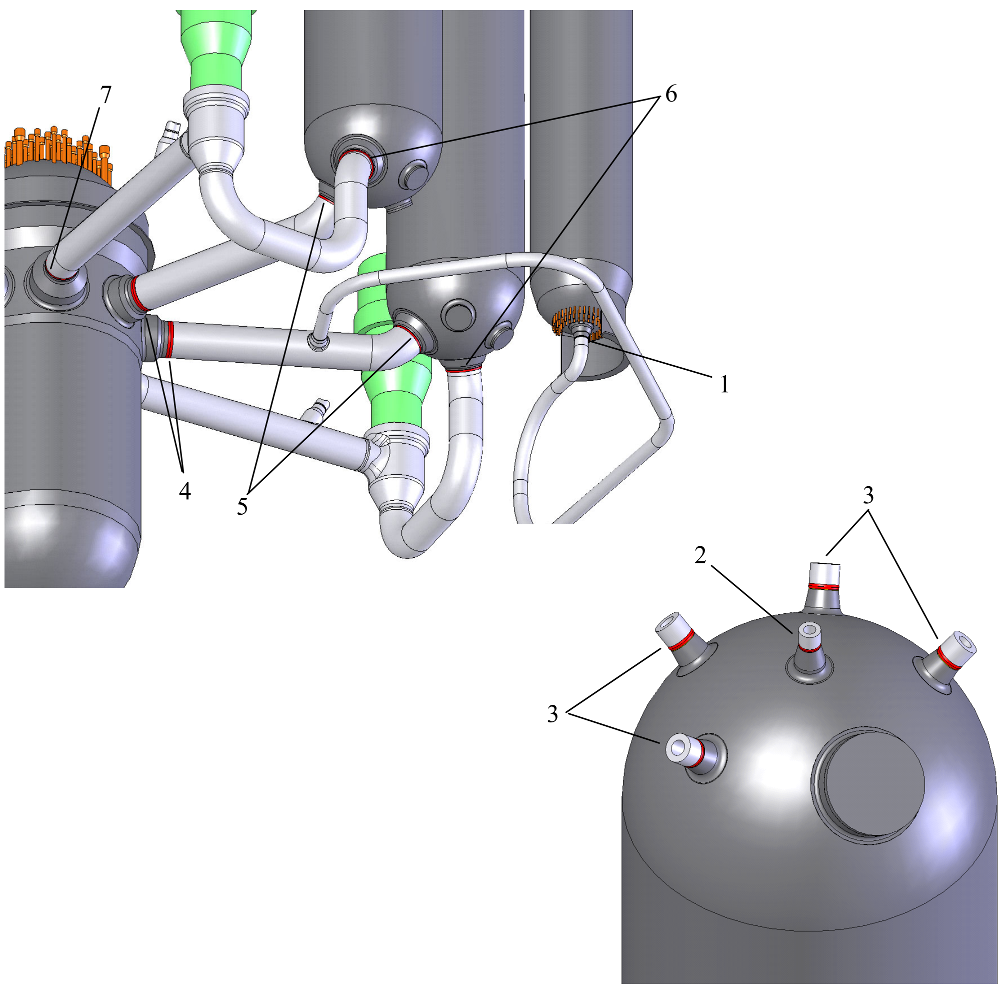


Figure 3-1
Typical Locations of Alloy 82/182 Butt Welds in Westinghouse Design Plants[1,2]

Application	Identification Number in Figure 3-2	Typical Temperature (°F)	Typical ID (inches)	Typical Number
Pressurizer				
- Surge Line Nozzle	1		10	1
- Spray Nozzle	2	643-653	3	1
- Safety/Relief Nozzles	3		5	2-3
RCS Hot Leg Pipe				
- Surge Line Nozzle	4		10	1
- Shutdown Cooling Outlet Nozzle	5	600	10	1
- Drain Nozzle	6		2	1
RCS Cold Leg Pipe				
- RCP Inlet Nozzles	7[3]		30	4
- RCP Outlet Nozzles	8[3]		30	4
- Safety Injection	9	549-560	10	4
- Pressurizer Spray Nozzles	10		2.25	2
- Letdown/Drain Nozzles	11		1.3	4[4]
- Charging Inlet Nozzle	12		1.3	2

1. Figures only show locations in pipes greater than 1" NPS and operating at temperatures greater than about 550°F.
2. Some plants with original reactor vessel closure heads have CEDM/ICI nozzles with Alloy 82/182 nozzle-to-flange butt welds.
3. One plant does not have Alloy 82/182 welds at reactor coolant pump.
4. One plant has 8 cold leg letdown/drain nozzles.

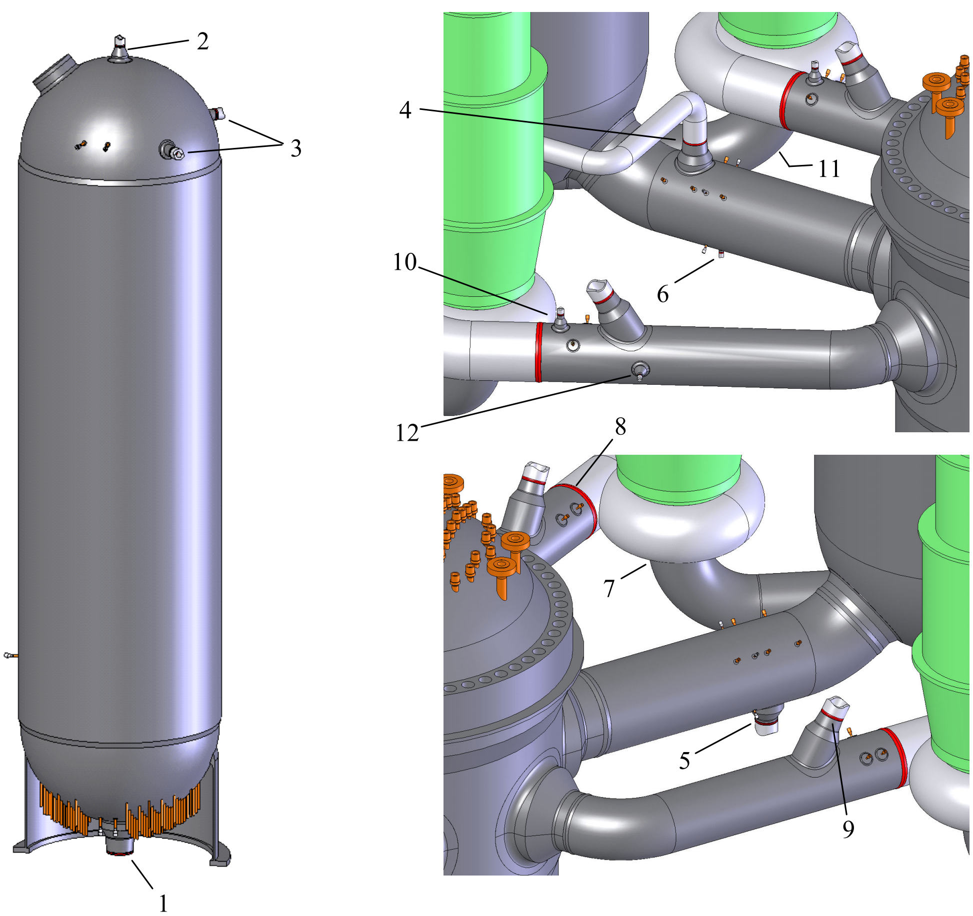


Figure 3-2
Typical Locations of Alloy 82/182 Butt Welds in Combustion Engineering Design Plants[1,2]

Application	Identification Number in Figure 3-3	Typical Temperature (°F)	Typical ID (inches)	Typical Number
Pressurizer				
- Surge Line Nozzle	1	650	10	1
- Spray Nozzle	2		4	1
- PORV Nozzle	3		2.5	1
- Safety Relief Nozzles	4		2.5-3	2
Reactor Vessel[2]				
- Core Flood Nozzle	5	577	14	2
RCS Hot Leg Pipe				
- Surge Line Nozzle	6	601-605	10	1
- Decay Heat Nozzle	7		12	1
RCS Cold Leg Pipe				
- RCP Inlet Nozzles	8	557	28	4
- RCP Outlet Nozzles	9		28	4
- High Pressure Injection Nozzles	10		2.5	4
- Letdown/Drain Nozzles	11		1.5-2.5	4
Core Flood Tanks				
- Outlet Nozzle	12	RT	14	2
- Pressure Relief	13		2	2

1. Figures only show locations in pipes greater than 1" NPS and operating at temperatures greater than about 550°F.
2. As of July 2004, there are two remaining B&W plants that have reactor vessel closure heads with Alloy 600 CRDM nozzles and Alloy 82 nozzle-to-flange butt welds (69 4" welds at temperature < 605°F).

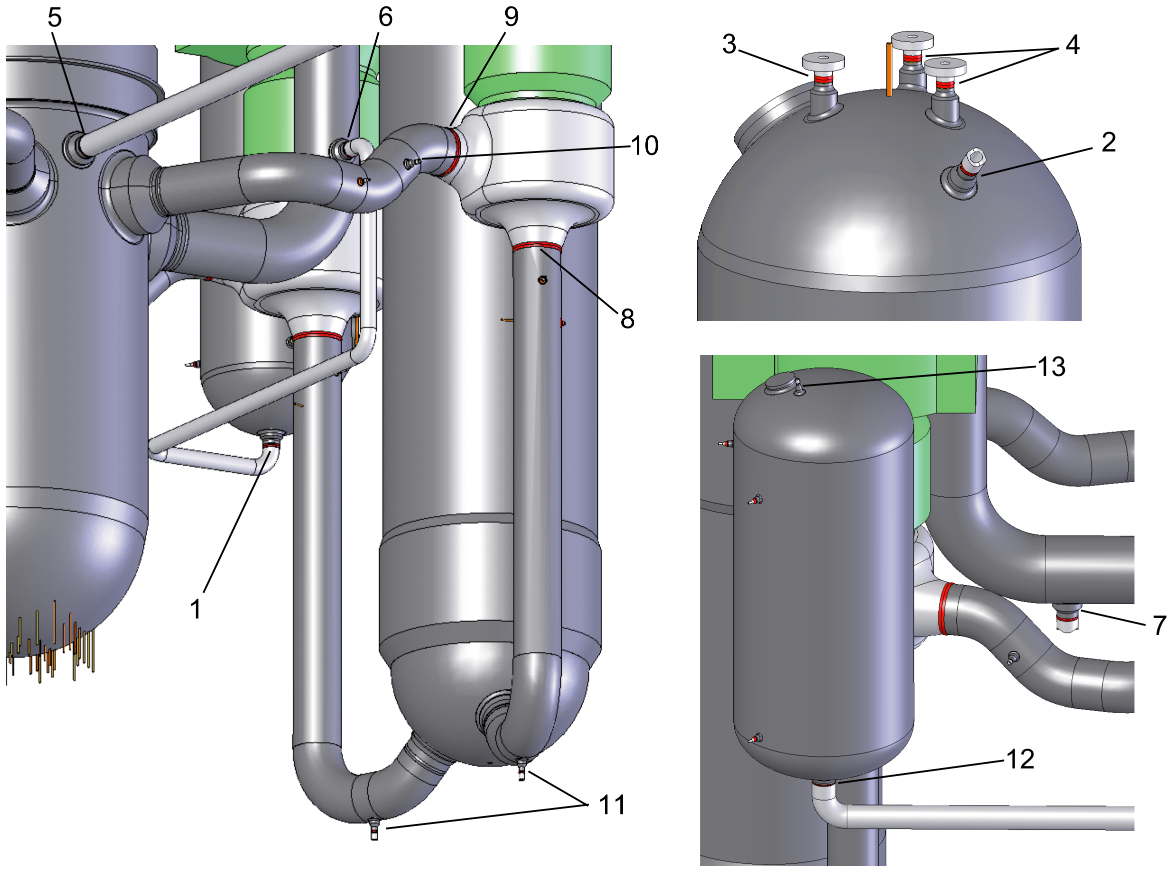


Figure 3-3
Typical Locations of Alloy 82/182 Butt Welds in Babcock & Wilcox Design Plants[1]

4
INSPECTION REQUIREMENTS, CAPABILITY AND RESULTS THROUGH MID 2004

The following is a review of current butt weld inspection requirements, current status of butt weld inspection technology as it relates to the probability of detecting butt weld flaws, inspection results through the Fall 2003 refueling outages, and conclusions regarding the condition of Alloy 82/182 butt welds based on the inspections performed to date.

4.1 ASME Code Section XI Inspection Requirements

To date, utilities have largely followed ASME Code Section XI inspection requirements for the subject locations.

	Pipe Size	Type of Inspection Required
- Welds	≥ 4 Inch NPS	Visual, Surface and Volumetric
- Welds	> 1 Inch NPS and < 4 Inch NPS	Visual and Surface
- Welds	≤ 1 Inch NPS	Visual

Table IWB-2500-1 of Section XI requires that 100% of dissimilar metal (DM) vessel nozzle-to-safe end welds (Category B-F), and 100% of dissimilar metal piping welds (Category B-J), be inspected at 10 year intervals. As noted in Section 3 of this report, essentially all of the key Alloy 82/182 pipe welds are dissimilar metal welds joining low-alloy steel nozzles to stainless steel pipe. Accordingly, most of the Alloy 82/182 butt welds have been inspected to the visual, surface or volumetric examination requirements noted above, depending upon the nominal pipe size. However, some plants have eliminated a portion of their dissimilar metal butt weld inspections as part of risk-based ISI programs.

4.2 Flaw Detection Capability

The following is a summary of the visual, surface and volumetric flaw detection capabilities.

4.2.1 Visual Examination

Visual inspections are a proven method for detecting small leaks of borated water. Visual inspections have proven to be a reliable method of finding small leaks from butt welds (V.C. Summer and Tsuruga 2), CRDM nozzles, pressurizer heater sleeves, RPV bottom head nozzles, and small diameter instrument nozzles. As indicated in Section 8 of this report, the industry recommended in January 2004 that all Alloy 82/182 butt weld locations should be subjected to a bare metal visual inspection or other equivalent examination, within the next two refueling outages with priority given to inspecting the highest temperature (pressurizer and hot leg) welds during the next outage in order to verify that there are no leaks [30]. Plants that have performed such an inspection during the last refueling need not repeat the inspection.

4.2.2 Surface Examination

Liquid penetrant examination of the external surface of a weld is capable of detecting through-wall flaws or outside surface initiated flaws. While surface examinations are capable of detecting through-wall cracks from the outside surface, visual inspections for boric acid leakage are expected to provide equally good detection of through-wall cracks. Visual, ECT or liquid penetrant examinations from the outside surface cannot detect part through-wall PWSCC cracks or subsurface cracks.

ECT examinations of the inside surface, where PWSCC cracks initiate, are only practical on the reactor vessel inlet and outlet nozzle butt welds since the inside surfaces of most butt welds are not accessible. Through 2004, the reactor vessel inlet and/or outlet nozzles at three domestic plants, including V.C. Summer, have been inspected by surface examination techniques from the inside surface.

4.2.3 Volumetric Examination: Experience Prior to About 1990

All dissimilar metal (DM) welds in pipes 4" NPS and greater, including those containing Alloy 82/182, in categories B-F and B-J, have been volumetrically examined every 10 years, following the requirements of ASME Section XI unless the inspections had been eliminated as part of a risk based ISI program. Ultrasonic examination methods (UT) are used predominantly for this examination. Radiography has also been used, but not as extensively as UT. Dissimilar metal welds pose an inspection challenge due to the microstructure of the weld combined with access constraints and weld geometry features [31].

The need for improving ultrasonic examination technology for austenitic piping, including DM welds, became evident during the early 1980s when extensive stress corrosion cracking [IGSCC] was discovered in BWR stainless steel piping systems [32]. In many cases, piping welds that had passed examination leaked very soon afterward, showing that cracks could escape detection using ultrasonic methods in practice at that time. During this same period, several international round robin exercises were completed [33] that showed large scatter in performance among inspection teams. This experience created an impetus to improve ultrasonic examination technology. Also at this time, formal requirements for demonstrating the performance of inspection procedures and personnel came into effect, but only for BWR piping inspections [34]. The BWR piping examination experience spurred improvements of UT instrumentation, procedures, and personnel training and performance was formally assessed and documented. Since no instances of similar cracking had been reported in PWR units, there was no corresponding effort to demonstrate performance for PWR piping inspection at that time [35].

However, the UT technology improvements that arose from the BWR experience contributed to improving the technology applied to PWR units although there were no regulatory requirements at the time to demonstrate capability for PWR applications [36].

4.2.4 Volumetric Examination: Improvements After 1990

General performance demonstration requirements first appeared as Appendix VIII to the 1989 edition of Section XI of the ASME Boiler and Pressure Vessel Code [33]. Appendix VIII requires demonstration of the capability to detect, discriminate, and size defects by examination of realistic mockups containing intentional defects with well-known size and location. Essential variables used in the performance demonstrations are recorded and become part of the qualification record. Supplements in Appendix VIII address specific components such as piping welds, vessel welds, vessel nozzles, bolting, etc. Supplement 10 of Appendix VIII addresses UT of dissimilar metal welds, and was incorporated into 10CFR50.55a requiring implementation by November 22, 2002. All dissimilar metal weld examinations after that date have been required to be performed with Appendix VIII qualified procedures and personnel. Thus, incorporation of Supplement 10 into the rule introduced formal performance demonstration requirements for PWR piping DM weld inspections.

Discovery of a leak from the V.C. Summer hot-leg weld in 2000, and the associated UT and ECT experience, showed that the geometry of the weld can dramatically affect the reliability of UT for examinations conducted from the pipe inside surface. Other experience, including Supplement 10 qualification results, confirmed the importance of knowing the weld configuration to enable adequate preparation for the examination. For examinations performed from the outside surface, the weld and nozzle geometry, and the roughness or waviness of the surface, have a particularly strong influence on the examination effectiveness.

The industry responded to these events with further improvements of UT technology coupled with intense efforts to qualify procedures and personnel to Supplement 10 for PWR applications. The qualification to Supplement 10 was modified to include challenging weld configurations such as were encountered at V.C. Summer to ensure that procedures and tooling address the range of inside surface contours. These experiences have identified the most effective techniques and practices and these practices are being incorporated into production examination procedures [37]. In many situations, procedures and equipment in place prior to Supplement 10 implementation had to be modified to improve performance to meet the new requirements. Another practical outcome of implementation of Appendix VIII, in addition to documentation of performance relative to standards, is formal documentation of procedure limitations. That is, the qualification record specifically documents the range of conditions, such as surface roughness or waviness, for which the procedure is qualified. This enables the licensee to identify where the procedures would not be effective and allows assessment and application of alternatives to address the limitations. This kind of formal documentation was not available prior to implementation of Appendix VIII. The most significant limitations pertain to surface conditions and weld configurations that preclude effective scanning. Licensees can assess the applicability of qualified procedures only if the site-specific surface conditions and as-built weld configurations are known.

4.2.5 Volumetric Examination: Summary Status

PWR DM weld examinations conducted prior to implementation of Appendix VIII were performed with a variety of techniques and with a range of effectiveness that is not possible to accurately quantify [32,37]. A review of industry experience [37] shows several instances where cracking, including circumferential cracking, escaped detection. The lack of detailed documentation of NDE capability prior to Supplement 10, coupled with the lack of detailed information on as-built weld configurations and access, makes it impossible to definitively characterize the capability of procedures applied in past examinations. However, it must be emphasized that while qualification requirements have driven some recent improvements, adoption of Appendix VIII did not lead to a step increase in capability over that of previous technology. Rather, examination capability has been continually improving in response to service experience and the availability of technology innovations. Appendix VIII is the latest major improvement in a history of continuous capability improvement. Implementation of Supplement 10 to Appendix VIII has resulted in development and application of improved procedures for UT detection and characterization of PWSCC in pipe butt welds. Structural integrity assessments can be made with confidence for those situations in which a qualified UT procedure can be applied.

In summary, while volumetric inspections prior to about 2002 may not have had the same detection capability or pedigree as inspections subsequent to about 2002, they have provided some assurance, in combination with the results of visual and surface examinations, that significant PWSCC is not widespread in dissimilar metal welds.

4.3 Inspection Results Through Spring 2004 Refueling Outages

Alloy 82/182 butt welds in domestic PWR plants have been inspected as specified by Section XI of the ASME Code and by visual inspections for boric acid leakage. As noted above, these inspections have involved visual inspections, surface examinations and volumetric examinations. Similar inspections have been performed at PWR plants worldwide. As of the end of July 2004 there have only been a small number of cases of part-through-wall axial flaws limited to the widths of the welds, two cases of leaks occurring from axial flaws and one case involving a short shallow circumferential flaw. The two leaks from axial flaws were detected by visual inspections for boric acid. None of the indications posed a significant safety concern at the time of detection.

4.4 Conclusions Regarding Butt Weld Condition

The following conclusions can be drawn from the above experience:

- There is potential for PWSCC of Alloy 82/182 butt welds
- A significant number of butt welds have been inspected per plant ISI programs
- The inspection capability has improved significantly over the past two years
- There is no evidence of widespread PWSCC of Alloy 82/182 butt welds at present

- All major PWSCC incidents involving Alloy 82/182 butt welds to date have been associated with significant weld repairs
- No significant safety concern has resulted from butt weld PWSCC to date
- The few locations listed in paragraph 3.4 involving Alloy 600 safe ends or nozzles will require priority attention for two reasons. First, field experience has shown the potential for large through-wall circumferential flaws in the base metal heat affected zone. Second, axial cracks that initiate in the Alloy 82/182 weld metal may continue to propagate into the Alloy 600 safe end or nozzle. However, as indicated in paragraph 3.4, Alloy 600 safe ends in applications greater than 1" NPS, and operating temperatures greater than 550°F, are limited to pressurizer spray nozzles in B&W design plants and several nozzles in Palisades. In the case of the B&W pressurizer spray nozzle safe ends, the critical length for axial flaws is greater than the combined length of the Alloy 82/182 butt welds and the Alloy 600 safe ends.

5
BACKGROUND TECHNICAL INFORMATION

The following is a brief discussion of the factors that contribute to PWSCC in Alloy 82/182 butt welds. This includes consideration of PWSCC initiation, crack growth rates in Alloy 82/182 weld metal, the role of several key design and fabrication related factors on crack initiation and growth, welding residual and operating stresses in Alloy 82/182 butt welds, and the most likely flaw orientation. This background information serves as input to the deterministic and probabilistic assessments in Sections 6 and 7 of this report.

5.1 Crack Initiation: Material Susceptibility, Tensile Stress and Environment

As has been well documented, nickel-chromium-iron Alloy 600s materials are susceptible to PWSCC in PWR primary coolant environments [38]. Three conditions must exist simultaneously for PWSCC to occur 1) susceptible material, 2) tensile stresses, and 3) an aggressive environment.

5.1.1 Susceptible Material

Extensive work has been performed to determine the factors that affect PWSCC susceptibility of Alloy 600 base metals. This work has shown that two main factors are the carbon content and the annealing temperature. Specifically, to achieve good resistance to PWSCC, the annealing temperature must be high enough to result in carbides being deposited predominantly at the grain boundaries rather than distributed throughout the grains.

Laboratory test work by Bettis and KAPL has shown that, while the material microstructure is significantly different, Alloy 82 weld metal has about the same susceptibility to PWSCC as Alloy 600 base metal [39,40] assuming identical test conditions. EdF and AREVA conducted a comprehensive series of tests of weld alloys with chromium contents ranging from 14% to 30% [41]. The results of the four types of tests (bend tests in doped steam, CERTs in primary water, reverse U-bends (RUBs) in primary water, and constant load tests in primary water) were consistent and showed that susceptibility to PWSCC decreases as the chromium content increases. This suggests that Alloy 182 (Cr 13-17%) will be more susceptible to PWSCC than Alloy 82 (Cr 18-22%).

In summary, Alloy 82 and 182 weld metals are known to be susceptible to PWSCC based on laboratory tests and previously summarized field experience, with Alloy 182 material being the more susceptible of the two due to its lower chromium content.

5.1.2 Tensile Stress

Sustained high tensile stresses are required for PWSCC. There are two main sources of tensile stresses—operating condition stresses produced by pressure, temperature and other mechanical loads, and welding residual stresses. The operating pressure, operating temperature and external piping loads produce primary and secondary stresses. These stresses are included in the plant design calculations and must be maintained within the specified ASME Code Section III allowables. However, higher stresses are typically created during fabrication by shrinkage forces that develop as the weld cools. The welding stresses, commonly called welding residual stresses, are typically higher than the operating stresses and tend to be the dominant driving force for PWSCC initiation and crack growth. Welding residual stresses are not addressed in the ASME Code Section III stress limits.

For a typical un-repaired PWR plant butt weld that is formed by application of weld beads from the outside surface, finite element stress analyses show high tensile hoop stresses in the outer part of the weld and lower hoop stresses approaching the inside surface. Axial tensile stresses can also develop on the inside surface. However, the axial stresses tend to be relatively low tension or compression in PWR welds that typically have a small diameter to thickness (D/t) ratio.

Paragraph 5.4 provides further discussion of welding residual and operating stresses in typical Alloy 82/182 butt welds, including the potentially detrimental effect of weld repairs.

5.1.3 Environment

Experience has shown that the water chemistry and temperature in PWR plant primary coolant systems is capable of supporting PWSCC. The general experience is that, for materials of equal PWSCC susceptibility with equal applied tensile stress, the time to crack initiation is a function of the operating temperature. Locations that operate at higher temperatures, such as in the pressurizers, typically exhibit cracking sooner than locations that operate at lower temperatures, such as in the RCS cold legs. For typical PWR plant pressurizer (653°F), hot leg (600°F) and cold leg (550°F) temperatures, and a thermal activation energy of 50 kcal/mole for crack initiation, the multipliers on time to PWSCC for hot leg and cold leg locations relative to pressurizer locations are 7.7 and 63.7 respectively. If predictions are based on crack growth rate data, the activation energy can be taken as 31 kcal/mole and the corresponding multipliers on time are 3.5 and 13.1 respectively.

While the primary coolant hydrogen and lithium concentrations can affect PWSCC initiation and growth, studies have shown only a small effect over the ranges through which these parameters can be adjusted within the EPRI Primary Water Chemistry Guidelines [42]. Zinc addition on the other hand has been used in several plants and can have a significant beneficial effect on PWSCC crack initiation. Zinc addition could potentially be used in more plants in the future as a PWSCC remedial measure, including for Alloy 82/182 butt welds, and as a means of reducing radiation exposure.

5.2 Crack Growth Rates

Crack growth rate models for Alloy 82/182 butt welds have been established from laboratory tests and the reasonableness of the model for Alloy 182 weld metal has been confirmed by experience at Ringhals 3 where repeat inspections were performed to determine crack growth.

5.2.1 Deterministic Crack Growth Rate Model Established by MRP

The MRP recently developed a deterministic crack growth model for Alloy 82/182 weld metal materials based on a statistical evaluation of the worldwide set of available laboratory test data for these materials using controlled fracture mechanics specimens [19]. Similar to the process used by the MRP to develop a deterministic crack growth rate equation for Alloy 600 base metal [18], the MRP screened the test procedures, reviewed the test results, produced a statistical model and developed a recommended deterministic equation. An international panel of experts convened by EPRI provided detailed input to the MRP during its evaluations of Alloy 600 and Alloy 82/182.

The MRP deterministic curves for Alloy 82/182 weld metal are shown in Figure 5-1. Based on the statistical evaluation of the laboratory data:

- The deterministic crack growth rate curve recommended for Alloy 82 weld metal is about 1.5 times higher (at K = 30 MPa√m) than the crack growth rate recommended for Alloy 600 material.
- The deterministic crack growth rate curve recommended for Alloy 182 weld metal is about 3.8 times higher (at K = 30 MPa√m) than the crack growth rate recommended for Alloy 600 material.

The MRP equation for Alloy 182 weld metal at 325°C (617°F) is:

$$\dot{a} = 1.5\times10^{-12} K^{1.6} \quad \text{(m/s where } K \text{ is in units of MPa}\sqrt{\text{m}})$$

The MRP equation for Alloy 82 weld metal at 325°C (617°F) is:

$$\dot{a} = \left(1.5\times10^{-12}/2.6\right) K^{1.6} = 5.77\times10^{-13} K^{1.6} \quad \text{(m/s where } K \text{ is in units of MPa}\sqrt{\text{m}})$$

The MRP database of laboratory crack growth rate data indicates that the crack growth rate for Alloy 82 is on average 2.6 times lower than that for Alloy 182, so the MRP curve for Alloy 82 is 2.6 times lower than the curve for Alloy 182. For crack propagation that is clearly perpendicular to the dendrite solidification direction, the MRP recommends that a factor of 2.0 lowering the crack growth rate may be applied to the curves for Alloy 82 and Alloy 182.

The general form of the MRP equation for Alloy 82/182 weld metal is as follows:

$$\dot{a} = \exp\left[-\frac{Q_g}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]\alpha f_{alloy} f_{orient} K^{\beta}$$

where:

$\dot{a}$	=	crack growth rate at temperature T in m/s (or in/h)
Q_g	=	thermal activation energy for crack growth
	=	130 kJ/mole (31.0 kcal/mole)
R	=	universal gas constant
	=	8.314×10^{-3} kJ/mole-K (1.103×10^{-3} kcal/mole-°R)
T	=	absolute operating temperature at location of crack, K (or °R)
T_{ref}	=	absolute reference temperature used to normalize data
	=	598.15 K (1076.67°R)
α	=	power-law constant
	=	1.5×10^{-12} at 325°C for $\dot{a}$ in units of m/s and K in units of MPa$\sqrt{}$m (2.47×10^{-7} at 617°F for $\dot{a}$ in units of in/h and K in units of ksi$\sqrt{}$in)
f_{alloy}	=	1.0 for Alloy 182 and 1/2.6 = 0.385 for Alloy 82
f_{orient}	=	1.0 except 0.5 for crack propagation that is clearly perpendicular to the dendrite solidification direction
K	=	crack tip stress intensity factor, MPa$\sqrt{}$m (or ksi$\sqrt{}$in)
β	=	exponent
	=	1.6

For comparison, Figure 5-1 also shows the earlier MRP-21 [22] curve for Alloy 182 weld metal. This curve, published in 2000, was based on a smaller set of data available at the time and did not result from a systematic statistical assessment. Note that unlike the earlier MRP-21 curve, the apparent stress intensity factor threshold for the new MRP deterministic model [19] is taken as zero, meaning that crack growth is assumed to occur whenever the crack tip stress intensity factor is positive.

5.2.2 Crack Growth Measured for Ringhals 3 Butt Weld

Repeat measurements were made of the depths of two axial cracks in one of the Ringhals 3 reactor vessel outlet nozzle-to-safe-end Alloy 182 butt welds [10,12,43]. Both cracks had initial depths of 9 ± 3 mm in 2000. After approximately 8,000 hours of operation, Crack 1 had a depth of 13 ± 3 mm and Crack 2 had a depth of 16 ± 3 mm. The best estimate growth rates for these two cracks, and the estimated ranges to account for uncertainty in inspection depth sizing, adjusted to 325°C (617°F) using an activation energy of 31 kcal/mole, are plotted on Figure 5-1. These data are in good agreement with the crack growth rate curves recently established by the MRP based on laboratory test data [19].

5.3 Effect of Design and Fabrication Practices on Crack Initiation and Growth

Several design and fabrication practices are believed to have a significant effect on crack initiation and growth in Alloy 82/182 butt welds. These are as follows:

5.3.1 Welding Processes and Materials

Alloy 82 weld metal is uncoated wire that is used for manual or machine gas tungsten arc welding (GTAW) with a cover gas. Alloy 182 weld metal is supplied in the form of coated electrodes used for shielded metal arc welding (SMAW). A main chemistry difference between these two materials is that Alloy 82 material has 18-22% chromium and Alloy 182 material has 13-17% chromium. The higher chromium content of Alloy 82 weld metal results in better resistance to PWSCC initiation and crack growth as noted in paragraph 5.1.1 and 5.2.1.

Most of the Alloy 82/182 butt welds are of the basic configuration shown in Figure 5-2. Alloy 182 buttering was applied to the low-alloy steel nozzle or pipe, the buttering received post weld heat treatment (PWHT) with the low-alloy steel component, then the final Alloy 82 or 182 weld was made to the stainless steel pipe or safe-end. This design eliminated the need to stress relieve the low-alloy steel nozzle/pipe after welding to the stainless steel pipe, and avoided exposing the stainless steel material to stress relief temperatures where it could possibly become sensitized. There are several variations of this basic configuration, especially for the case of reactor vessel nozzle to pipe welds in Westinghouse plants, and they are discussed in the supporting NSSS specific documents.

In most cases, the buttering was applied manually using the SMAW process with Alloy 182 weld metal. The butt weld root passes, and often 2 or 3 additional passes, were typically applied using manual or machine GTAW with Alloy 82 filler metal. The welds were then completed using the manual SMAW process with Alloy 182 filler metal in earlier plants or by GTAW using Alloy 82 filler metal in some later plants. Alloy 132, which has the same chromium content as Alloy 182, was used for the butt weld in the Tsuruga 2 pressurizer relief nozzle butt weld that developed a leak.

Based on the above, most Alloy 82/182 butt welds are expected to have at least some of the more susceptible Alloy 182 weld metal in contact with the primary coolant where it can lead to PWSCC crack initiation and growth. For example, most welds containing Alloy 82 weld root passes, or completed using automated Alloy 82 machine welds, will still have some exposed Alloy 182 weld metal in the buttering.

5.3.2 Weld Repairs

The Alloy 82/182 butt welds were inspected, and repaired if necessary, during fabrication. One of the supporting documents to this summary assessment report (MRP-114) documents several repair scenarios [27]. Weld repairs can be performed from the inside surface or the outside surface. It is interesting to note that the two cases involving leaks from Alloy 82/132/182 butt welds (V.C. Summer and Tsuruga 2) and approximately 45% through-wall axial flaw at TMI-1 all involved extensive weld repairs.

In many cases, plants do not have information on the actual repairs performed to Alloy 82/182 butt welds or have not retrieved, documented and evaluated the repairs. However, some plants that do have these records indicate that repairs were common, including some welds being repaired multiple times and some repairs having a significant arc length. As will be addressed in paragraph 5.4, weld repairs can result in high inside surface tensile residual stresses.

5.3.3 Machining Inside Surface After Welding

Many nozzles from the pressurizer surge line size and below were machined on the inside surfaces after welding. This machining has the potential to remove crack starters at the weld root and improve inspectability. However, cold work due to machining on the inside surface and the heat input from turning operations can result in tensile residual stresses in the cold worked material. The cold work and tensile residual stresses due to machining are typically limited to a shallow depth.

The shallow depth of the tensile residual stress induced by machining may explain why many of these nozzles have not developed leaks. Specifically, cracks which initiate and propagate through the zone of tensile residual stress may not result in a high enough stress intensity factor in the remaining weld metal for significant crack growth once the crack extends beyond the cold worked region. Assuming a conservative tensile stress of 40 ksi in a weld at a typical 0.003" depth for a cold worked surface produced by machining, the stress intensity factor would be:

$$K = 1.1\sigma\sqrt{\pi a} = 1.1(40\text{ ksi})\sqrt{\pi(0.003\text{ in})} = 4.3\text{ ksi}\sqrt{\text{in}}\text{ or }4.7\text{ MPa}\sqrt{\text{m}}$$

In summary, while machining can cold work the surface and create local tensile residual stresses, the resultant stress intensity factor may be too low to result in significant crack growth once the crack grows out of the cold worked layer. It should be noted that this situation, involving machining after welding, is significantly different from that in CRDM nozzles where material that is cold worked to final dimensions by machining is then subjected to high strains during the J-groove welding process.

5.3.4 Welding and Grinding on Inside Surface

Fabrication records show that some larger size hot and cold leg piping butt welds were back gouged on the inside surface and then welded and ground again on the inside surface. As will be discussed in paragraph 5.4, welding on the inside surface after completion of the entire weld has the potential to increase the inside surface tensile stresses and thereby increase the potential for PWSCC. Further, grinding at this location could result in crack starters due to the cold work and high thermally induced surface residual stresses.

5.4 Welding Residual and Operating Stresses

Finite element analyses have been performed of typical Alloy 82/182 butt welds ranging from 30 inch diameter reactor vessel outlet nozzles to 1 inch NPS instrument nozzles. The matrix of welds analyzed in report MRP-106 by Dominion Engineering, Inc. is shown in Figure 5-3. Figure 5-2 shows the finite element model used for the pressurizer surge nozzle butt weld analysis. Complete details of the analysis models, methods and results are provided in the MRP-106 [26]. The analysis approach was to first simulate the butt weld by modeling multiple weld passes. Each pass consisted of a thermal analysis to determine the temperature distributions during weld cooling and a structural analysis to calculate the stresses produced during weld pass cooling. After completion of welding, the joint was subjected to conditions simulating hydrostatic test pressure, and then subjected to the operating pressure and temperature. Primary piping loads during operation were not included since they vary considerably from plant-to-plant. Stresses due to primary piping loads can be added to the other operating stresses by linear superposition. The validity of this approach was confirmed by finite element analyses.

In addition to the as-designed case, where the weld is built up from the inside to the outside surface, cases were run for weld repairs made to the inside surface of the weld after completion of the entire weld from the outside. As will be shown, this can create significant tensile residual stresses on the inside of the weld. Cases were run for repairs that run completely around the weld (360°) and for repair lengths of 30°, 60° and 90° of the weld circumference.

Figure 5-4 shows welding residual and operating condition stresses for the as-designed case for a typical pressurizer surge nozzle with no inside surface weld repair. The figure also shows operating condition stresses with an assumed 360° inside surface weld repair. Axial stresses are plotted on the left and hoop stresses are plotted on the right. Also reported for each case are the maximum axial and hoop stresses on the inside surface for the two operating condition cases. The color contours for the stress plots in Figures 5-4 and 5-5 are shown in Figure 5-6. These results show that the maximum hoop stresses exceed the maximum axial stresses under operating conditions and that a weld repair to the inside surface after completing the main weld significantly increases both the axial and hoop stresses on the inside surface. These results are for a 2D axisymmetric finite element model.

Figure 5-5 shows results for a 3D finite element model of a typical pressurizer surge nozzle with weld repairs performed for partial arcs of 30°, 60°, and 90°. These results show similar stresses to the case for a 360° repair, although the maximum axial stresses tend to be slightly higher.

5.5 Comparison of Calculated Welding Residual Stresses to Generic Model

Crack growth analyses have typically been performed using welding residual stresses that have been established based on analysis and test work for generic butt welds. Figure 5-7 shows results reported in the Journal of Pressure Vessel Technology [44] and used for the Westinghouse (MRP-109) and AREVA (MRP-112) analyses of Alloy 82/182 butt welds [21,24].

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In summary, the finite element analyses show that a normal weld completed from the outside surface with no repairs results in favorable welding residual and operating stresses from the standpoint of PWSCC initiation and growth. However, any repairs to the inside surface or deep part-circumferential repairs to the outside surface can result in through thickness welding residual and operating stress distributions capable of producing through-wall axial cracks and some circumferential cracking (see paragraph 6.4 for discussion of crack growth following weld repairs.)

5.6 Flaw Orientation: Axial vs. Circumferential

The flaw orientation is a key factor in butt weld safety assessments. Axial PWSCC flaws are limited to the width of the Alloy 82/182 weld metal since PWSCC will not occur in the low-alloy steel and stainless steel materials at each end. Flaws can only grow into the adjoining PWSCC resistant materials at a slow rate by fatigue. This model is consistent with experience at V.C. Summer and Tsuruga 2 as shown in Figures 2-1.a and 2-2 and with experience in the hot leg pressurizer surge line nozzle at TMI-1. It should be noted that this self arresting feature does not exist for the small number of cases where the Alloy 82/182 weld is connected to an Alloy 600 safe end or nozzle. See paragraph 3.4 for reference to locations with Alloy 600 safe ends. However, if axial cracks were to propagate into the Alloy 600 safe end, the crack growth rate would be expected to decrease due to the lower crack growth rates in Alloy 600 base metal relative to weld metal and possibly to a reduction in stress as the crack grows away from the high stress weld region.

Part-circumferential flaws that extend through-wall, although not yet seen to date in Alloy 82/182 weld metal, can potentially grow to significant length before leakage would be detected by traditional on-line detection methods such as inventory balances. As shown in Section 6, these leaks will be detected with significant margin before reaching critical flaw sizes.

As discussed in paragraph 5.6.2, part-depth 360° circumferential flaws are not expected to ocur.

The purpose of the following paragraphs is to review available information relating to possible flaw orientations.

5.6.1 PWR Field Experience

Cracking of Alloy 82/182 butt welds in PWR plants has been limited to V.C. Summer, Ringhals 3, Ringhals 4, Tsuruga 2, TMI-1 and possibly Tihange. All of these indications have been axial with the exception of a short (2 inch long), shallow (≈0.20 inch deep) circumferential crack associated with the through-wall axial crack which leaked at V.C. Summer. The shallow circumferential crack arrested when it reached the low-alloy steel nozzle base metal.

While not in the weld proper, there have been two cases of part-circumferential flaws that extend through-wall in the weld heat affected zone of Alloy 600 base metal (see Palisades and ATR in paragraph 2.1).

5.6.2 BWR Field Experience

BWR plants experienced SCC of piping early in plant life and the flaw orientations can shed some light on the potential for circumferential cracks to develop in PWR plant butt welds.

The MRP sponsored GE Nuclear Energy to document cracking experience in BWR piping. The result of this work is summarized in report MRP-57 [20]. Figure 5-12 shows plots of the lengths and depths of axial cracks and the arc-lengths and depths of circumferential cracks discovered in BWR pipe butt welds. The data show that axial cracks can grow to significant length if not arrested by some resistant material transition such as low-alloy or stainless steel for the case of PWSCC in PWR plants. The data show that most of the circumferential flaws had arc lengths less than about 75°. The reason for the short arc length was not explored in detail, but weld repairs may be a contributing factor as discussed in paragraph 6.4.

The case of the 360° part-depth crack at Duane Arnold has received significant attention and is often used as an example of why 360° part-depth cracks cannot be ruled out. A cross section through the Duane Arnold crack is shown in Figure 5-13 [45]. Crack initiation and growth were attributed to the presence of a fully circumferential crevice that led to development of an acidic environment because of the oxygen in the normal BWR water chemistry, combined with high residual and applied stresses as a result of the geometry and nearby welds. The water chemistry conditions that contributed to cracking at Duane Arnold do not exist for the case of Alloy 82/182 butt welds in PWR plants.

5.6.3 Finite Element Stress Analysis

The finite element modeling described in paragraph 5.4, and described in detail in report MRP-106, shows that hoop stresses (*residual plus operating*) are predicted to exceed axial stresses (*residual plus operating*) at high stress locations on the inside surface such that cracks are most likely to start out axially oriented in the absence of circumferentially oriented defects. These results also show that the through-wall stress distributions favor axially oriented cracks such as were discovered at Ringhals, V.C. Summer, Tsuruga 2, and TMI-1. However, the analysis results show locations of high axial stress on the inside surface for the case of repaired welds that could possibly support initiation and growth of circumferential cracks.

5.6.4 Summary Regarding Probable Crack Orientation

In summary, the above review of PWR field experience, BWR field experience, and finite element stress analysis results suggests that most PWSCC flaws in Alloy 82/182 butt welds are likely to be axially oriented. Additional work on this topic in paragraph 6.4 shows that deep circumferential flaws are likely to be limited to the lengths of arc which are repaired from the inside surface or are affected by deep repairs from the outside surface.

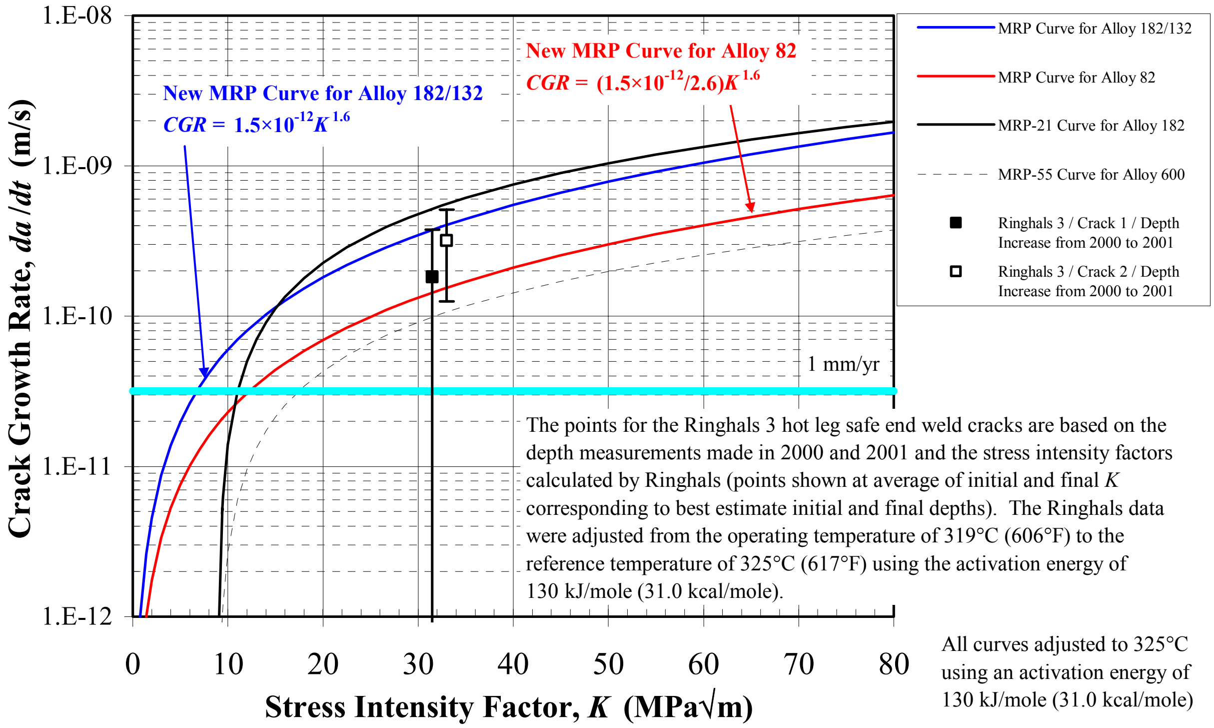
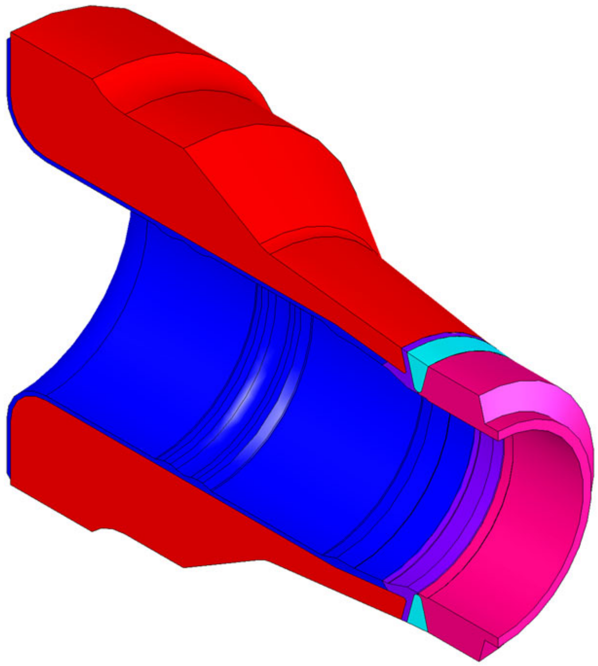
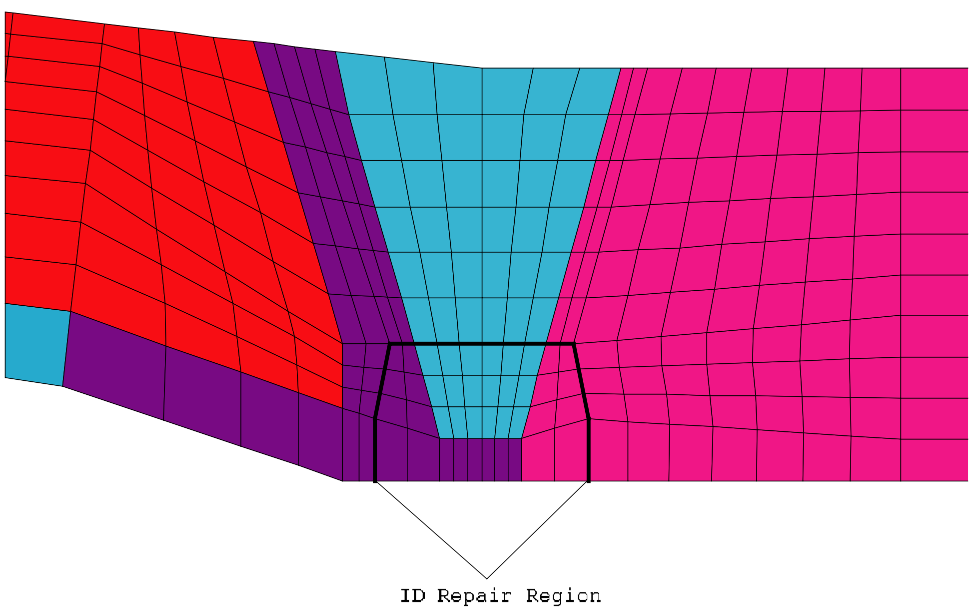


Figure 5-1
Butt Weld Crack Growth Rate Models, Including Estimates of Crack Growth Rates Based on Ringhals 3 Measurements

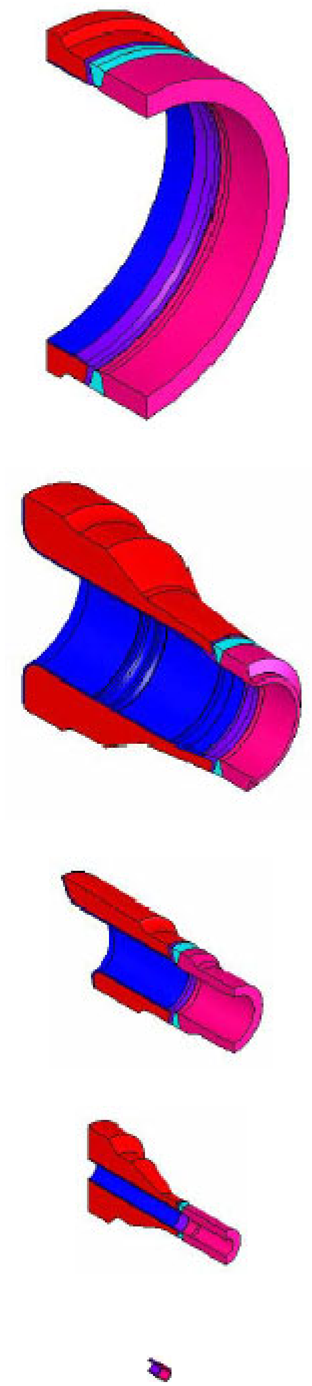


a. Typical Pressurizer Surge Line Nozzle



b. Finite Element Model

Figure 5-2
Typical Alloy 82/182 Butt Weld and Finite Element Model



RPV Nozzle
30" ID, 2.3" Wall

Pressurizer Surge Nozzle
10" ID, 1.66" Wall

Pressurizer Safety Relief Nozzle
5" ID, 1.59" Wall

HP Injection Nozzle
2" ID, 0.75" Wall

Instrument Nozzle
1" ID, 0.179" Wall

Figure 5-3
Matrix of Butt Welds for Finite Element Analysis with Typical Dimensions

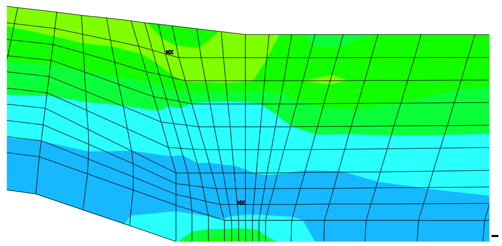
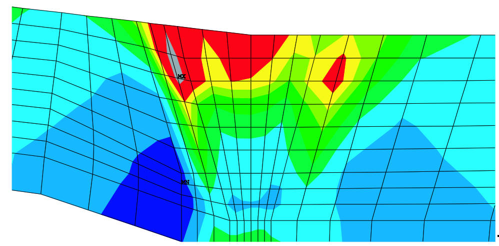
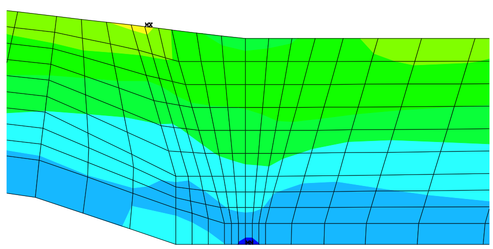
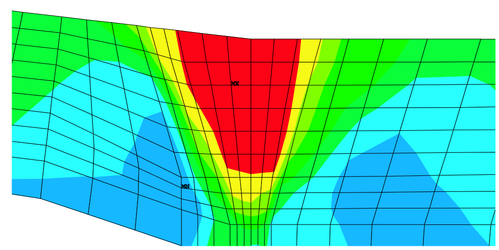
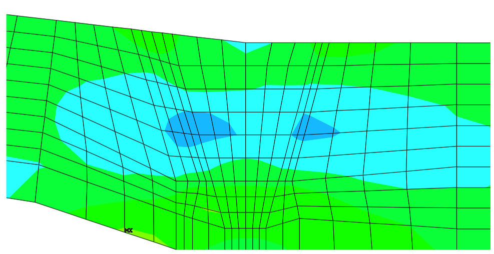
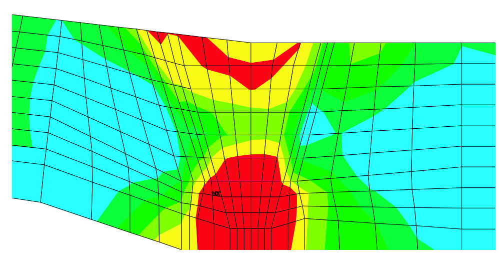
Condition	Axial Stress	Hoop Stress
Welding Residual Stresses	 25.1 ksi Max Inside Surface Stress	 11.7 ksi Max Inside Surface Stress
Welding Residual and Operating Stresses – As Designed	 -2.7 ksi Max Inside Surface Stress	 9.0 ksi Max Inside Surface Stress
Welding Residual and Operating Stress With 360° Inside Surface Repair	 32.5 ksi Max Inside Surface Stress	 52.8 ksi Max Inside Surface Stress

Figure 5-4
Welding Residual and Operating Stresses in Typical CE Pressurizer Surge Nozzle Butt Weld with and Without 360° Inside Surface Weld Repair (data from MRP-106)(color contours shown in Figure 5-6)

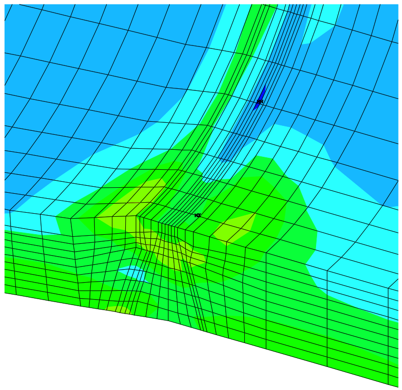
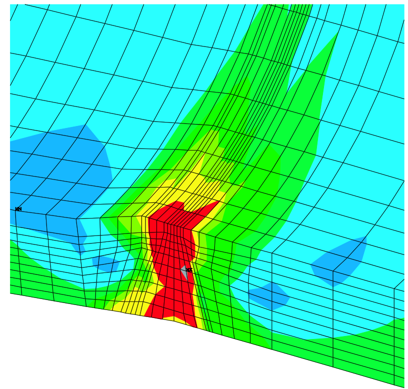
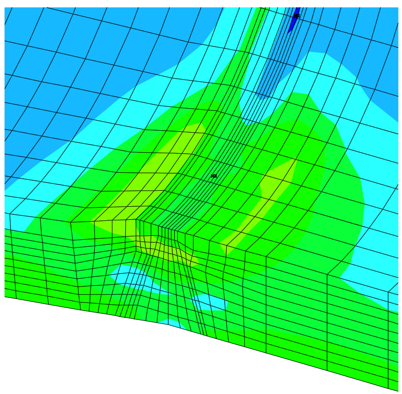
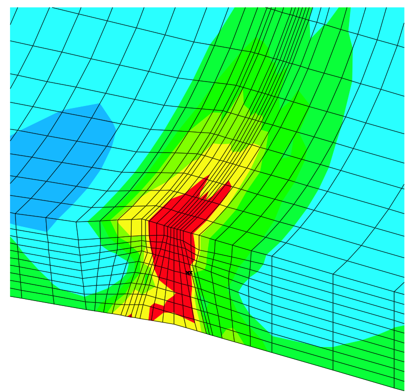
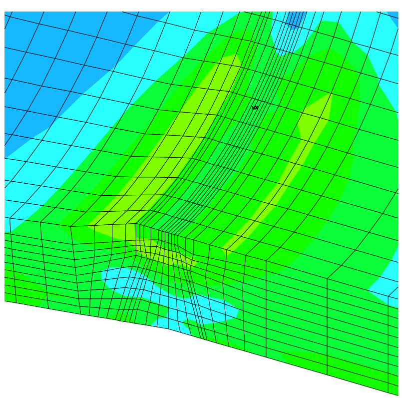
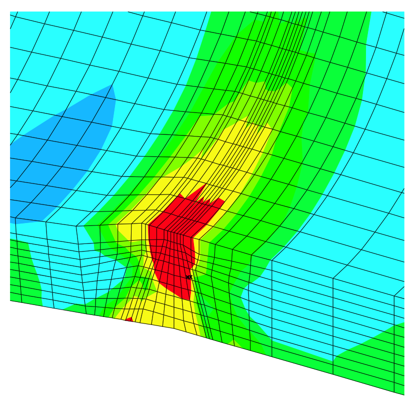
Condition	Axial Stress	Hoop Stress
Welding Residual and Operating Stress 30° Arc Inside Surface Repair	 39.9 ksi Max Inside Surface Stress	 54.6 ksi Max Inside Surface Stress
Welding Residual and Operating Stress 60° Arc Inside Surface Repair	 38.6 ksi Max Inside Surface Stress	 52.6 ksi Max Inside Surface Stress
Welding Residual and Operating Stress 90° Arc Inside Surface Repair	 38.6 ksi Max Inside Surface Stress	 52.9 ksi Max Inside Surface Stress

Figure 5-5
Welding Residual and Operating Stresses in Typical CE Pressurizer Surge Nozzle Butt Weld with Part-circumferential Inside Surface Weld Repairs (data from MRP-106)(color contours shown in Figure 5-6)

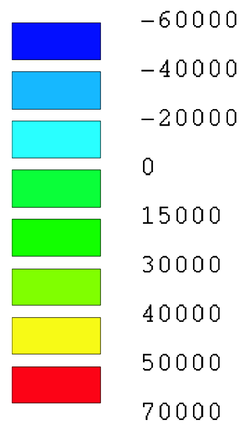


Figure 5-6
Color Contour Definitions (psi) for Stress Plots in Figures 5-4 and 5-5

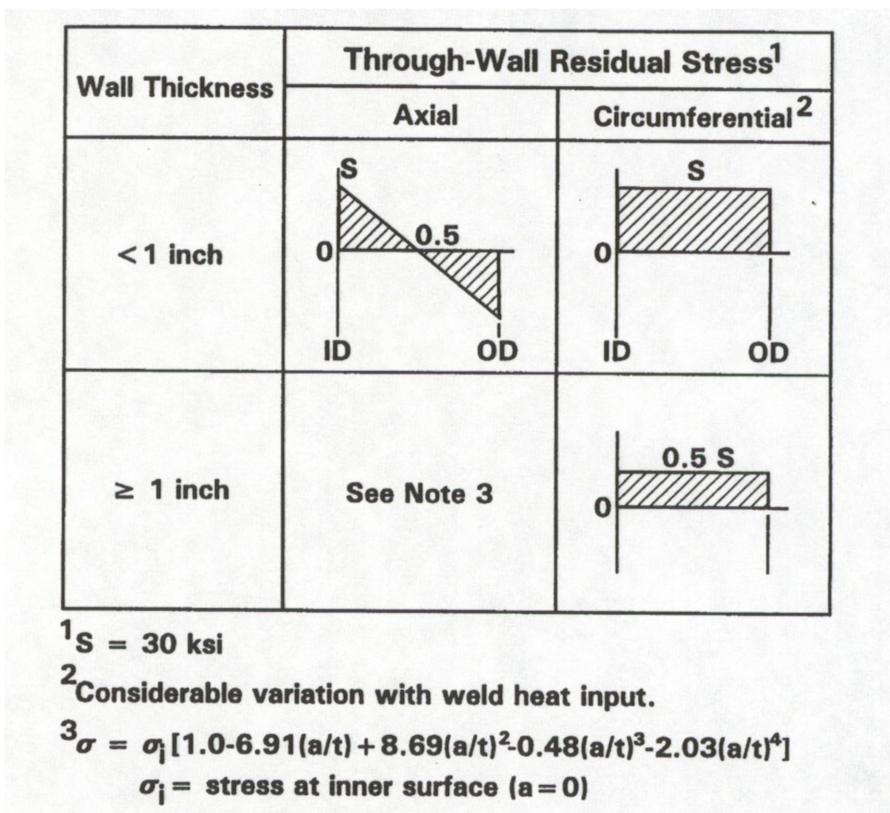


Figure 5-7
Generic Welding Residual Stress Distributions for Austenitic Pipe Welds [44]

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Figure 5-8
Through-Wall Residual Hoop Stress Without Weld Repair (from MRP-106)

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Figure 5-9
Through-Wall Residual Axial Stress Without Weld Repair (from MRP-106)

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Figure 5-10
Through-Wall Residual Stress with 360° Inside Surface Weld Repair (from MRP-106)

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Figure 5-11
Through-Wall Operating Stress in Typical Pressurizer Surge Nozzle with and Without Repairs (as designed and ID repair data from MRP-106)

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Figure 5-12
Lengths and Depths of Axial and Circumferential Cracks in BWR Internals Butt Welds (data from MRP-57 [20])

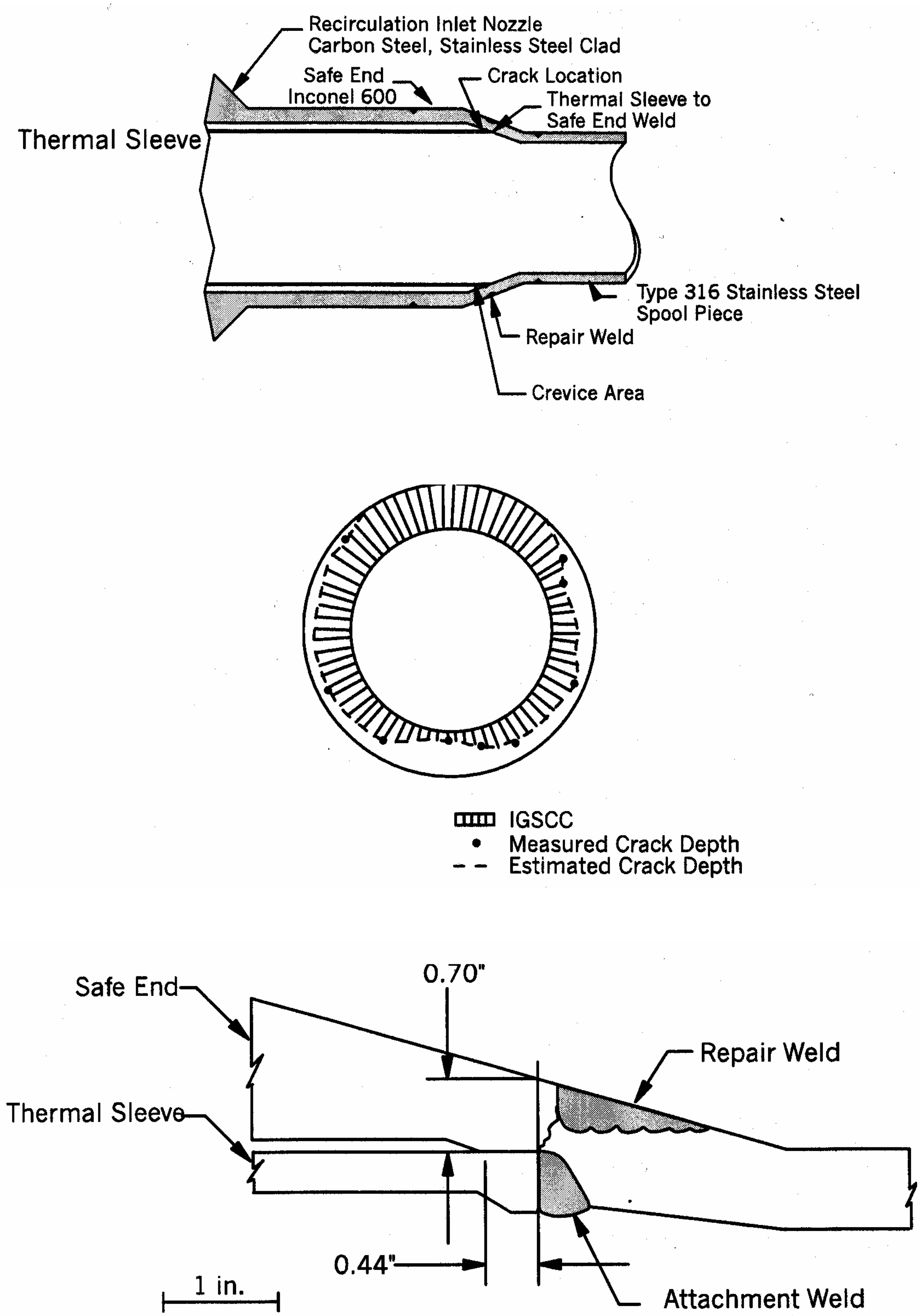

Figure 5-13
Cross Section Through 360° Part Depth Crack at Duane Arnold [45]

6 DETERMINISTIC SAFETY ASSESSMENT

This section describes deterministic analyses which demonstrate that Alloy 82/182 pipe butt welds in PWR plants are tolerant of large size axial and circumferential flaws and that the nondestructive examinations, visual inspections and existing on-line leak detection methods provide margin against rupture. Deterministic analyses for a range of weld locations, designs and loadings are provided in the supporting technical reports by the NSSS vendors. Analyses to assess the probability of rupture due to flaws reaching critical size are described in Section 7.

6.1 Critical Size of Axial and Circumferential Cracks

Westinghouse (MRP-109) and AREVA (MRP-112) have performed analyses to determine the critical flaw sizes for a range of Alloy 82/182 butt welds in plants from all three NSSS suppliers. These calculations are documented in vendor safety assessment reports [21,24]. Critical flaw size calculations were based on ASME Code Section XI methodology.

6.1.1 Critical Lengths for Axial Flaws

As shown in Figures 2-1 and 2-2, axial PWSCC flaws are limited to the width of the Alloy 82/182 weld material for cases involving welds between low-alloy steel nozzles and stainless steel or clad low-alloy steel pipe. Experience has confirmed that the PWSCC cracks arrest when they reach the PWSCC resistant low-alloy steel and stainless steel materials. Therefore, the maximum axial crack lengths are limited to a few inches at most (much less than the critical axial flaw length), except for the small number of cases involving Alloy 600 safe ends or Alloy 600 pipe/tube (CRDM and BMI nozzles) where axial cracks initiating in the weld could potentially propagate into the Alloy 600 base metal, although at a reduced rate. See paragraph 3.4 for locations with Alloy 600 safe ends.

The driving forces for axial flaws are the welding residual and internal pressure hoop stresses. Bending moments and axial forces on the pipe do not contribute to the critical length of axial through-wall flaws.

Westinghouse calculations (MRP-109) for the critical length of through-wall axial flaws were performed using pipe burst pressure theory. AREVA calculations (MRP-112) for the critical length of axial through-wall flaws were performed using the limit load methodology of Section XI, Appendix C extended to the case of through-wall flaws by ASME Code Case N-513 [46].

6.1.2 Critical Lengths for Through-Wall Circumferential Flaws

Analyses for the critical lengths of circumferential flaws include dead weight loads, thermal stratification loads, and safe shutdown earthquake loads in addition to internal pressure. The axial forces, bending moments and torsional moments were taken from the latest plant analyses including changes resulting from steam generator replacements, steam generator snubber elimination, steam generator center of gravity and weight revisions, and power uprating. Calculations were performed for a range of plants to identify the limiting condition for each location. Details of these calculations are provided in the vendor reports (MRP-109 and MRP-112).

6.1.3 Critical Depth for Part-Depth 360° Circumferential Flaws

Calculations for critical part-depth 360° circumferential flaws were performed using the same input parameters as for the through-wall circumferential flaws.

6.1.4 Analysis Results for Controlling Plants

Table 6-1 summarizes the analysis results for the plants with the smallest critical flaw sizes for each NSSS vendor. In some cases data are provided for two plants for each nozzle type and vendor since one nozzle does not have the lowest margin for all crack types. The data in Table 6-1 show that the butt welds have significant margin for all three types of cracks.

Figures 6-1.a, 6-1.b and 6-1.c show typical analysis results for the Westinghouse Plant "C" RPV outlet nozzle. Similar plots are provided for many, but not all, of the other cases in the vendor reports. The three sample plots show the following:

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6.1.5 Conclusions Regarding Critical Flaw Size

The data in Table 6-1 show that Alloy 82/182 butt welds in domestic PWR plants can tolerate significant size axial and circumferential flaws while maintaining structural integrity.

6.2 Growth of Axial Flaws

No calculations have been performed for the growth rate of axial flaws since analysis results in paragraph 6.1 demonstrate that the maximum lengths of through-wall axial cracks which are limited to the width of the Alloy 82/182 weld, are significantly less than the critical flaw lengths noted in Table 6-1.

While no calculations have been performed, propagation of axial flaws from initiation to leakage in less than an operating cycle is possible since hoop stresses in the welds can be high and crack growth rates in Alloy 182 weld metal are approximately 3.8 times higher than in Alloy 600 base metal at $K = 30$ MPa√m (see paragraph 5.2 and Figure 5-1). However, as noted in the previous paragraph, this does not pose a risk of rupture since the maximum crack length is much less than the critical crack length.

6.3 Growth of Circumferential Flaws – Without Weld Repairs

Westinghouse and AREVA completed analyses of crack growth prior to the MRP finalizing a crack growth rate model for Alloy 82/182 weld materials. Accordingly, these analyses were performed using the weld crack growth rate model in report MRP-21 [22] which includes an apparent stress intensity factor threshold of 9 MPa√m below which cracks will not propagate by PWSCC. These original analyses are summarized in paragraph 6.3.1. Westinghouse and AREVA performed check calculations after the MRP issued its final crack growth rate model in October 2003 [19]. The effect of the change is addressed in paragraph 6.3.2.

6.3.1 Calculations Performed Using Stress Intensity Factor Threshold of 9 MPa√m

Westinghouse and AREVA both calculated growth of circumferential cracks using a similar approach. The first step was to calculate the time for a crack to grow from a depth that will support crack growth to through-wall. The second step was to calculate the time required for a through-wall circumferential crack to grow from a length that results in a predicted 1 gpm leak rate under normal operating conditions to the critical length reported in paragraph 6.1.

Accordingly, these calculations provide an estimate of the time to create a leak and the time for a detectable leak to grow to critical size. Figures 6-2.a and 6-2.b show typical analysis results for the case of the pressurizer surge nozzle in Westinghouse plant “F”. The calculations are based on the following main assumptions:

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6.3.2 Calculations Using EPRI-MRP Model Without Stress Intensity Factor Threshold

Westinghouse performed an assessment for three locations at the two most limiting Combustion Engineering plants using the MRP crack growth rate model for Alloy 82/182 weld metal [19] and the results are documented in a letter report [23]. The data show that the times for cracks to grow through-wall are reduced from previous calculations described in paragraph 6.3.1 due to a stress intensity factor threshold of zero and higher crack growth rates for low stress intensity factors (K) as shown in Figure 5-1. However, the times for cracks to grow from a 1 gpm or 10 gpm leak to critical length are increased. The increase results from the fact that the new crack growth rates are lower than the original model rates at higher K levels. In both cases, the calculations were performed using the assumed initial flaw sizes from the earlier analyses.

AREVA conclusions [25] are similar to Westinghouse conclusions, i.e., the time for a flaw to grow to 75% through-wall is decreased and the time to grow from a 1 gpm leak to critical size is increased from those calculated using a threshold stress intensity factor value of 9 MPa√m.

In summary, the most important parameter from a safety standpoint, i.e., the calculated time for a flaw to grow from a length that produces a 1 gpm leak to the critical through-wall length, increases. This provides additional time to monitor for leakage and take corrective action, and thereby reduces the probability of core damage.

6.4 Growth of Circumferential Flaws – with Weld Repairs

Analyses were performed by Structural Integrity Associates, Inc. to calculate the growth of 360° and partial arc circumferential cracks in welds that have been repaired from the inside surface [27]. The intent of this work was to determine how cracks could potentially grow through-wall in a weld repaired region and the potential for crack growth beyond the area of the weld repair. This work was based on finite element stress analyses described in paragraph 5.4.

6.4.1 Locations and Weld Repairs Analyzed

Analyses were performed for the case of the reactor vessel outlet nozzle and the pressurizer surge nozzle described in paragraph 5.4. Analyses were performed for inside surface weld repairs of 30°, 60°, 90° and 360°.[1] The weld repair depths for the reactor vessel outlet nozzle and the pressurizer surge nozzle welds were 0.35 inches (15.2% through-wall) and 0.55 inches (33% through-wall) respectively. Figure 6-4 shows a typical crack geometry assumed for the analyses and angular locations where stresses and crack tip stress intensities were analyzed.

6.4.2 Applied Stresses

The operating condition stresses reported in paragraph 5.4 include the welding residual stresses plus stresses due to internal pressure and differential thermal expansion between the low-alloy steel, Alloy 82/182 and stainless steel pipe. The stresses in paragraph 5.4 do not include other applied piping loads such as deadweight and piping thermal expansion since these loads are not a function of the joint geometry and can vary from plant-to-plant. Accordingly, the Structural Integrity Associates analyses were performed using applied piping loads of 50%, 75%, 100% and 125% of the material design stress intensity (Sm). The design stress intensity for SA-376 Type 304N is 17.6 ksi at 650°F. Of this applied piping stress, 1 ksi was assumed to be an axial membrane stress and the remainder assumed to be an axial bending stress based on a sampling of some PWR plant piping stresses. The axial bending stress was applied in two configurations. The first case conservatively assumed that the maximum bending stress applies throughout the entire pipe cross section. The second case assumed that the bending stress is a maximum at the centerline of the weld and decreases with angle from the center of the repaired area.

6.4.3 Stress Intensity Factors

Stress intensity factors were calculated at selected angles from the edge of the repairs as shown in Figure 6-5. The stress intensity at each cross section is calculated using the equation [47]:

$$K_{\mathrm{I}} = \left[\sigma_0 i_0 + \sigma_1 i_1 a + \sigma_2 i_2 a^2 + \sigma_3 i_3 a^3 + \sigma_{\mathrm{gb}} F_{\mathrm{b}}\right]\sqrt{\pi a}$$

where:

1 As shown in Figure 5-11, deep partial-arc outside repairs would be expected to produce similar results as inside surface repairs.

K_I = stress intensity factor
a = crack depth measured from inside surface

i_0, i_1, i_2, i_3, and F_b are the influence coefficients for a given crack-depth-to-wall-thickness ratio, a/t, interpolated from reference tables [47].

σ_0, σ_1, σ_2, σ_3 are the curve fit coefficients of the residual stress plus pressure distributions of the form $\sigma = \sigma_0 + \sigma_1 x + \sigma_2 x_2 + \sigma_3 x_3$, where x = the distance from the inside surface

σ_{gb} is the global moment stress. The value of the global moment bending stress is assumed to vary from 0.5Sm to 1.25Sm in increments of 0.25Sm.

For purposes of the analysis it was assumed that the circumferential crack has a length-to-depth ratio (2*c*/*a*) of 6:1.

6.4.4 Stress Intensity Factor Distributions

The first step was to determine if the stress was tensile on the inside surface at the location of interest. If the stress on the surface was compressive it was assumed that a crack would not initiate. If a stress was tensile, then calculations were performed to determine the potential crack depth with arrest predicted to occur when the crack tip stress intensity factor dropped to zero. Typical analysis results are shown in Figures 6-5.a and 6-5.b.

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- Content Deleted – MRP/EPRI Proprietary Material

6.4.5 Analysis Results

The conclusions from the analyses of welds repaired from the inside surface are as follows:

- In all cases, if a flaw initiates within the weld repaired region, it is predicted to grow through-wall relatively quickly primarily due to the welding residual stresses. While calculations were not performed using the EPRI-MRP crack growth model, the effect of using the model would be to reduce the already short time for cracks to grow through-wall and slightly extend the length of the through-wall crack. This is the same conclusion reached in analyses by Westinghouse and AREVA described in paragraph 6.3.2.
- For 360° inside surface repairs, cracks are predicted to grow through-wall for all locations.
- For part-circumferential repairs, through-wall crack growth should be limited to the repaired region for piping loads < 1.0 Sm. For piping loads of 1.25 Sm, through-wall crack growth

could extend significantly beyond the repaired region, but these high sustained stresses are unlikely.

6.5 Multiple Crack Initiation

This section discusses the implications of multiple initiation sites in dissimilar metal butt welds.

6.5.1 Industry Experience

PWSCC of RCS butt welds in PWR plants has been very limited. Although cracking has been observed in other Alloy 600/82/182 locations such as the vessel top head penetrations and J-groove welds, the bottom head penetrations in pressurizers, and in one RPV bottom head, only limited cracking has occurred in large or intermediate diameter primary coolant piping butt welds. For the few cases where flaws have been identified in large or intermediate diameter piping component welds, the cracking has been essentially axial, and contained within the weld. The only incidence of circumferential cracking was at the V.C. Summer plant where a single short circumferential crack on the inside surface terminated when it reached the low-alloy steel vessel outlet nozzle material.

The most significant flaw identified at V.C. Summer was a short axial flaw that went through-wall resulting in a leak. Crack growth in the through-wall direction can be attributed to weld repairs performed during the fabrication that led to high local through-wall tensile hoop residual stresses in the weld repair as discussed in paragraph 5.3.2.

Even though no significant circumferential cracking has been observed to date in thick wall PWR primary coolant piping, the potential consequences of such cracks have prompted the industry to examine their likelihood and consequences. As discussed in paragraph 6.4, it is expected that flaws in the circumferential direction resulting from weld repairs will tend to grow preferentially in the through-wall direction, thus resulting in a leak, as opposed to growing in the circumferential direction at some partial depth.

6.5.2 PWSCC Associated with Multiple Inside Surface Weld Repairs

PWR primary coolant piping with thickness greater than approximately 1-inch, fabricated from austenitic stainless steel or nickel base alloys and welded from the outside surface, contains a weld residual stress distribution that promotes arrest of circumferential cracks within the pipe wall thickness. This as-welded residual stress distribution produces a compressive residual stress over a significant region of the wall thickness. This favorable residual stress distribution occurs for thick components when the welding is performed from the outside surface, or, for double sided welds, when the welding is completed on the pipe outside surface. This desirable distribution can be modified significantly, or even reversed, when weld repairs are performed to the inside surface following the completion of the girth weld, or when the girth weld is double sided and is completed from the pipe inside surface.

The extent of the modification of the as-welded residual stress distribution associated with inside surface repairs depends upon the depth and length of the repair. For circumferential inside surface repairs approaching 360° of circumference, with significant through wall extent, the residual stresses produced during the repair can completely reverse the as-welded residual stress distribution and produce a condition conducive to through-wall growth for cracks driven by PWSCC. In the limiting case, cracks associated with such an extreme repair could create a condition that could lead to long part-depth circumferential cracks. However, experience to date has not shown such behavior.

The situation for multiple repairs performed on the inside surface of the piping component can be complex. For inside surface repairs remote from each other, as would be the case for 180° separation of the repairs, the residual stress associated with one repair would be independent of the other repair. The through-wall stress distribution for each crack would approximate that for a single repair, and be entirely dependent upon the depth and circumferential extent of the repair. However, the residual stress in adjacent non-repaired regions would quickly approach that of the original, favorable weld residual stress distribution associated with the unrepaired butt weld. This indicates that the circumferential PWSCC growth will most likely be limited to the region(s) of the weld repair and will minimally impact the non-repaired region. It also explains why weld repaired areas will have flaws growing mostly in the through-thickness direction, resulting in leaks.

Even if inside surface repairs were to interact, the residual stress is principally produced by the final inside surface repair, as modified by the circumferential extent and depth of each repair. The PWSCC associated with one repair would slightly reduce the residual stress field for other potential crack locations (since the weld residual stress is a secondary, displacement driven stress). Consequently the effect of multiple repairs in a localized region most likely can be bounded conservatively by assuming one overall repair that encompasses (with regard to both depth and circumferential extent) the entire repaired region of the pipe.

Similarly, in cases where multiple initiation sites occur within a weld repair, the cracks would be expected to grow independently and tend to become through-wall before significant circumferential growth were to occur. Flaws that are in close proximity to each other would interact in terms of slightly relieving the residual stress and in this case these flaws could be combined using ASME Code Section XI proximity rules.

6.5.3 Summary

Circumferential cracking of Alloy 82/182 welds in PWR piping has been limited to one crack at V.C. Summer. This is consistent with the fact that hoop residual stresses are significantly higher than axial residual stresses such that axial cracks would occur preferentially, and only a few axial cracks have been detected by NDE or leakage. In addition, the final weld residual stress distribution for large diameter, thick-wall piping components welded using nickel-base alloys would promote crack arrest if circumferential cracks in girth-welded pipes were to grow in depth through PWSCC.

However, when inside surface repairs are performed on the piping component following completion of the girth weld, significant local changes in residual stress occur. In the case of multiple, discrete inside surface repairs, circumferential PWSCC growth will most likely be limited to region(s) of the weld repair and will minimally impact the non-repaired region. If multiple initiation sites were to occur in a pipe with extensive multiple repairs (or multiple initiations within a single repair) through-wall growth of one or more of the flaws would be observed. The ASME Section XI flaw proximity rules can be conservatively used to bound multiple cracks attributed to PWSCC for flaw assessment purposes.

For the extreme case of fully circumferential inside surface repairs, the final, as-repaired residual stress state could promote PWSCC initiation and growth, possibly through-wall and significantly around the circumference of the component. Even in this case, however, other factors relating to both PWSCC initiation and growth, such as complex effects of weld metallurgy and weld pass sequencing make it unlikely that circumferential cracks of uniform depth would develop. Thus it is expected that a flaw associated with such a significant repair would still grow locally through-wall and result in leakage.

Finally, given the high hoop stresses at both repaired and unrepaired locations, the most probable outcome is an axial flaw developing and propagating through wall to produce a visible leak prior to a circumferential crack growing to a long length at part depth.

Based on this discussion, the presence of postulated multiple initiation sites for PWSCC in Alloy 600 weld metals does not result in an added safety concern. Since through-wall crack growth would dominate, it is expected that such behavior would lead to detectable leakage.

6.6 Leak Rates

Leak rates have been calculated as a function of axial and circumferential flaw size by Westinghouse and AREVA. Results of the leak rate calculations are illustrated in Figures 6-1.a and 6-1.b and are reported for the controlling cases in Tables 6-2 and 6-3. The following is a summary of the leak rate calculation methodologies.

6.6.1 Westinghouse Leak Rate Calculations

Westinghouse has performed leak rate calculations (MRP-109) using methods that have been reviewed and approved by the NRC for LBB applications. These calculations use a two-phase flow model that takes into account surface roughness.

Leakage calculations for axial flaws are performed using internal pressure loading only and include the conservative assumption that axial flaws can’t grow in length beyond the extent of the Alloy 82/182 weld metal. Leakage calculations for circumferential flaws are performed using normal steady state internal pressure, deadweight and thermal expansion loads. Leakage calculations do not include short term seismic loads.

6.6.2 AREVA Leak Rate Calculations

AREVA leakage calculations (MRP-112) were performed using the AREVA proprietary computer code "KRAKFLO." This code has been used for B&W Owners Group LBB applications that have been reviewed and approved by the NRC. Leak rates have been calculated assuming IGSCC-type cracks considered representative of PWSCC-type cracks that are likely to occur in a PWR. "KRAKFLO" has been benchmarked to Battelle Columbus Laboratory's (BCL) Phase II experiments involving Alloy 82 IGSCC experiments [48]. The procedure involved calculating the crack opening areas for assumed flaw sizes and then calculating the leak rate using a two-phase model that takes into account the surface roughness and the number of turns within a PWSCC type crack.

Leak rates were calculated for various circumferential through-wall flaws using normal operating pressure, deadweight, and normal 100% power thermal loads. Leak rates were calculated for through-wall axial flaws using the steady state normal operating pressure.

6.7 Margin Between Leak Detection and Critical Flaw Size

The preceding paragraphs have demonstrated that, while there is potential for leaks to occur due to rapid crack growth rates, the cracks will most likely be axial in nature due to the dominant hoop stresses in both repaired and non-repaired welds. Axial PWSCC cracks that arrest when they reach low-alloy steel and stainless steel materials are limited to the length of the weld and do not pose a risk of rupture. Axial cracks will be detected prior to reaching critical flaw size by non-destructive examination prior to leakage occurring, or by visual inspections or leak detection systems after leakage has started. The two leaks that have occurred have fit this model, i.e., have been short axial cracks that have been limited to the width of the weld and have been discovered by visual inspections for leakage.

Analyses and field experience show that circumferential cracks are likely to be accompanied by axial cracks that will grow at a more rapid rate such that they will be detected by NDE or visual inspections for leakage prior to the circumferential cracks growing to the size that they produce a leak. In the unlikely event that circumferential cracks develop without accompanying axial cracks, analyses show that they are likely to be associated with, and limited to, weld repair locations, will grow through-wall, and then can be detected visually during refueling outages, or by on-line leak detection systems prior to reaching critical length.

While there is a possibility of a deep part-depth 360° circumferential crack developing due to long ID weld repairs, it is unlikely that these cracks will occur without accompanying axial cracks that lead to detectable leakage. Nondestructive examinations associated with 10 year ISI programs provide a sampling check to ensure that the risk of unidentified part-depth 360° circumferential cracks remains low.

6.8 Boric Acid Corrosion

Experience to date with leaks from Alloy 82/132/182 butt welds at V.C. Summer and Tsuruga 2 has shown no evidence of significant boric acid wastage of the low-alloy steel material adjacent to the welds. In fact, there has been no report of significant wastage resulting from any Alloy 600/82/182 PWSCC leak except for the cases of the Davis-Besse reactor vessel head where leakage was allowed to continue for over six years without the source being identified or corrective action taken [49,50,51], and the ANO-2 pressurizer heater sleeve where leak rates were higher than normally expected for PWSCC due to loads imposed on the cracked sleeve by swelling of a failed heater [52]. This good experience is attributed to the leaks having been identified by visual inspections at an early stage where the leak rate is too low to allow liquid to concentrate on the hot metal surfaces.

There are no directly applicable data to predict the rate of boric acid corrosion due to a small leak from a PWSCC crack in an insulated Alloy 82/182 pipe butt weld. However, the following is known:

- Neither of the two leaks from Alloy 82/132/182 type butt welds (V.C. Summer and Tsuruga 2) resulted in measurable boric acid corrosion.
- Of the 55 leaks from CRDM nozzles through June 2004, visible boric acid corrosion has been reported for only five [51]. Only the leak for Davis-Besse nozzle no. 3 produced a structurally significant amount of low-alloy steel wastage (i.e., significantly greater than 1 in^3). This is important from a risk standpoint since the upward facing annulus type environment associated with CRDM nozzles may be more conducive to creating high corrosion rate situations such as occurred at Davis-Besse than leaks from Alloy 82/182 butt welds.
- For a crack (axial or circumferential) confined to the weld metal, there is no risk of high wastage rates occurring due to the situation of a jet impinging on a low-alloy steel crevice or cavity, which is believed to have occurred at Davis-Besse, since the Alloy 82/182 weld metal is highly resistant to boric acid corrosion. This is evidenced by the fact that the J-groove weld metal at Davis-Besse was intact after corrosion of the large volume of low-alloy steel material and by laboratory tests that confirmed insignificant corrosion rates for Alloy 600 in concentrated boric acid environments [53].
- For an axial crack that reaches the low-alloy steel base metal, there is potential for erosion to create a crevice that could lead to Davis-Besse type conditions. However, the crack opening displacement is such that the crack will tend to remain tight at the Alloy 82/182 to low alloy steel interface, thereby likely preventing leakage from reaching the level that could cause local cooling to the point that concentration of boric acid could occur. Accordingly, this situation would be similar to that for a crack contained within the Alloy 82/182 weld metal.
- Based on the above, the risk of creating a Davis-Besse crevice-type situation is considered to be low. The greater concern with boric acid is that the borated liquid phase of a leak will come into contact with low-alloy steel material surfaces under conditions that will support high corrosion rates. For example, prior to there being concern over Alloy 600 PWSCC, there were several cases where leakage of hot primary coolant into insulated areas led to significant corrosion. As described in the EPRI *Boric Acid Corrosion Guidebook* [52], these

incidents resulted in corrosion of reactor coolant pump closure studs, reactor coolant pump closure flanges, RPV head studs, steam generator and pressurizer manway studs, valve bolting and packing yokes, etc.

- At present, the most applicable test data are for the case of small leaks of simulated primary coolant into insulated bolted flanges. These tests were performed for EPRI at Southwest Research Institute and are reported in Rev. 1 to the *Boric Acid Corrosion Guidebook* [52]. As shown in Figure 4-29 of the guidebook, maximum corrosion rates of 0.75-1.0 in/yr were found for leak rates of 0.01 gpm and maximum corrosion rates up to 1.75 in/yr were found for leak rates of 0.1 gpm. These corrosion rates are significant.

Based on the above, while the potential for boric acid corrosion cannot be ruled out, the potential for significant boric acid corrosion is considered to be very low. The low risk is the result of non-destructive examinations to ensure that here are no widespread problems with Alloy 82/182 butt welds in the fleet, visual inspections for boric acid leakage during outages, on-line detection for larger leak, practical experience with the two leaks at V.C. Summer and Tsuruga 2, and practical experience with other leaks from CRDM nozzles, pressurizer instrument nozzles, pressurizer heater sleeves, hot leg piping instrument nozzles, and reactor vessel bottom head instrument nozzles.

Table 6-1
Critical Flaw Size Assessment Summary

Location	NSSS	Plant	Burst Pressure for 2.5" Long Through-Wall Axial Flaw (ksi)	Critical Through-Wall Axial Flaw Length[1] (in)	Critical Through-Wall Circ Flaw Length (deg)	Critical 360° Part Depth a/t Ratio
PZR - Surge Line	Content Deleted – MRP/EPRI Proprietary Material					
PZR - Spray						
PZR - Safety/Relief						
HL – RPV Outlet						
HL – SG Inlet						
HL – Shutdown Cooling						
HL – Surge Line						
HL – Decay Heat						
CL – RPV Inlet						
CL – RPV Core Flood						
CL – SG Outlet						
CL – RCP Suction						
CL – RCP Discharge						

(1) These critical axial flaw lengths are much greater than the width of the Alloy 82/182 butt welds.
(2) PZR = Pressurizer, CL = Cold Leg, HL = Hot Leg

Table 6-2
Crack Growth Analysis of Part-Circumferential Through-Wall Flaws:
Westinghouse and CE Design Plants: Based on MRP-21 Crack Growth Rates

Location	NSSS	Plant	Time to Through-Wall 6:1 Aspect Ratio (years)	Time to Through-Wall 2:1 Aspect Ratio (years)	Time from 1 GPM to Critical Flaw Size (years)	Time from 10 GPM to Critical Flaw Size (years)
PZR - Surge Line	Content Deleted – MRP/EPRI Proprietary Material					
PZR - Spray						
PZR - Safety/Relief						
HL – RPV Outlet						
HL – SG Inlet						
HL – Shutdown Cooling						
HL – Surge Line						
CL – RPV Inlet						
CL – SG Outlet						
CL – RCP Suction						
CL – RCP Discharge						

Content Deleted – MRP/EPRI Proprietary Material

Table 6-3
Crack Growth Analysis of Part-Circumferential Through-Wall Flaws:
Babcock & Wilcox Design Plants: Based on MRP-21 Crack Growth Rates

Location	NSSS	Plant	Time from Initiation to 75% Through-Wall (years)	Time from 1 GPM to Critical Flaw Size (years)
PZR - Surge Line	Content Deleted – MRP/EPRI Proprietary Material			
PZR – Spray				
PZR – Relief				
HL - Decay Heat				
CL – RPV Core Flood				

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Content Deleted – MRP/EPRI Proprietary Material

Figure 6-1
Westinghouse Plant C Reactor Vessel Outlet Nozzle
(Limit Pressure and Moment vs. Crack Length)

Content Deleted – MRP/EPRI Proprietary Material

Figure 6-1
Westinghouse Plant C Reactor Vessel Outlet Nozzle
(Limit Pressure and Moment vs. Crack Length) (cont'd)

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Figure 6-2
Westinghouse Plant F Reactor Pressurizer Surge Nozzle
(Flaw Dimension vs. Time)

Content Deleted – MRP/EPRI Proprietary Material

Figure 6-3
Through-Wall Axial Stress Distribution for Temperature Loading (615°F) Only

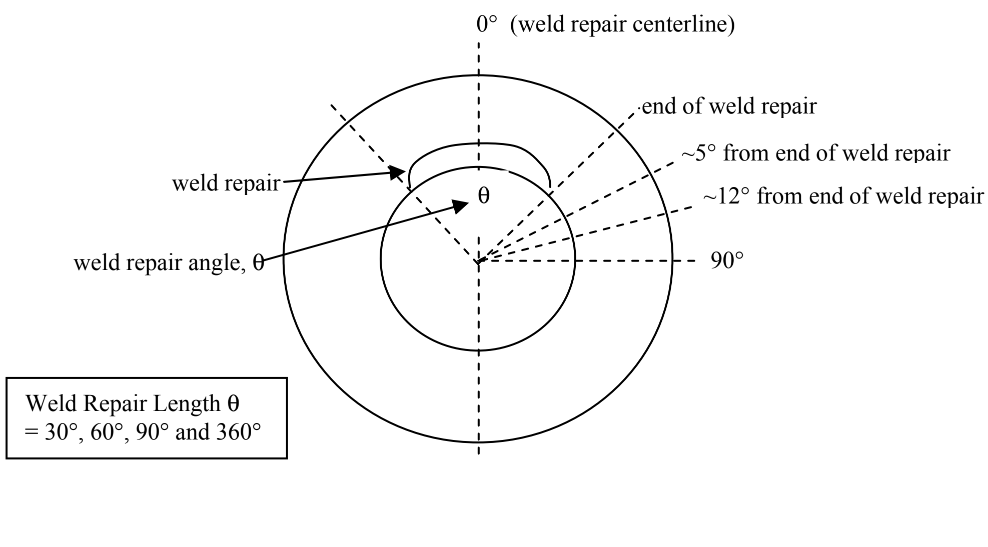

Figure 6-4
Typical Geometry Assumed for Analysis of Crack Growth at Weld Repair Locations

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Figure 6-5
Stress Intensity Factor for RPV Outlet Nozzle Weld
(Pipe Stress = 0.5Sm and Maximum Bending Stress Uniformly Applied)

7
PROBABILISTIC SAFETY ASSESSMENT

A probabilistic safety assessment was performed by Westinghouse for domestic Westinghouse, Combustion Engineering and Babcock & Wilcox design PWR plants using probabilistic fracture mechanics (PFM) methods. The following is a brief summary of this work. Detailed results are provided in MRP-116 [28].

The probabilistic safety assessment builds on the deterministic work reported separately for these units [21,24] and addresses the probability that a flaw could grow through the wall and could eventually lead to rupture and a resultant increase in core damage frequency. The evaluations documented in the report have been intended to cover all the Alloy 82/182 butt weld locations in operating PWRs in the USA. The deterministic results, as well as complementary work to provide input on the effects of repairs [26,27,54] and crack growth modeling [19], have been brought together in the risk report. The three goals of the risk analysis were the following:

- Quantify the probability of leakage from both axial and circumferential flaws
- Assess the impact of the calculated change in core damage risk from Alloy 182 cracking per the RG 1.174 guidelines [29]
- Develop a recommendation as to the adequacy of the current ASME Section XI inspection requirements for these regions

The PFM methodology used for the evaluations is consistent with that used in previous submittals that have been reviewed and approved by the NRC. This includes the Westinghouse Owners Group treatment of the probability of head penetration cracking [54,55,56] and the Westinghouse Owners Group risk-informed inspection approach for piping welds[57,58]. Key effects treated in this work include crack initiation, crack growth, criteria for failure of the pipe, and the consequences of a range of piping leak rates on the core damage frequency. Note that cracking in only the weld metal was considered in this study. There are a few cases where the safe end material is Alloy 600 instead of stainless steel, and these were not treated by this evaluation.

Since the existing PFM models for reactor vessel head penetrations [54,55,56] already included crack growth due to PWSCC, the new correlation for weld metal (Alloy 82, 132, and 182) developed by the MRP [19] was used directly. The existing PFM models for fatigue crack growth (FCG) for piping RI-ISI [57,58] were used directly for the PFM models for butt welds. Figures 14(a) and 14(b) of the Argonne National Laboratory (ANL) report [59] indicate that the FCG of Alloy 82/182, respectively, are best characterized as a factor on the Alloy 600 FCG in air. Analyses of this data are used to develop the mean value and uncertainty for the factor on weld FCG. The benchmarking process to address these enhancements is discussed in full in Section 4 of the risk report [28]. The conclusion is that the PFM models used to calculate the leak probabilities for axial and circumferential flaws in Alloy 82/182 butt welds in piping nozzles have been benchmarked with existing failure (small-leak) data and independently verified to produce accurate results.

The leak probability calculated for axial flaws, using PFM methodologies with a 10-year inspection, ranges from 5.0×10^{-5} to 1.7×10^{-2} at 40 years of plant life. The leak probability for a circumferential flaw with a 10-year inspection ranges from 2.7×10^{-8} to 2.0×10^{-4} at 40 years of plant life. Probabilities for larger leaks that would correspond to small, medium, or large Loss of Coolant Accidents would be smaller. Probabilities of leak for a 60-year life were generally somewhat higher than those for 40 years.

A comparison of axial versus circumferential leak probabilities shows that the axial probability is consistently higher than the circumferential probability, by more than two orders of magnitude. The axial flaw length would be limited in extent to the interface with material not susceptible to PWSCC, which is consistent with service experience. The evaluation considered this length to be equal to the thickness of the weld, which is a conservative assumption.

The results of the assessment showed that the change in total plant risk satisfied the RG 1.174 guidelines for "insignificant change" when considering core damage frequency for a 40-year plant life. Calculated core damage frequency point estimate values ranged from 1.85×10^{-8} to 8.74×10^{-8} per year based on a 40-year life. These values for total plant change in risk were determined by combining the worst-case leak probability for each location with a generic conditional core damage probability value of 3.0×10^{-3} and combining the contributions from the individual nozzles. The calculation for a plant-specific application would be lower. The consequences for large early release frequency would be approximately an order of magnitude lower than those for core damage, based on typical plant data. Therefore, the change in risk for large early release frequency would also be insignificant.

There are several items that contribute to the conservatisms in the calculated leak probabilities. Two that result in the greatest overall contribution are the treatment of weld residual stress and credit for leak detection. Residual stresses are represented as the peak through-wall value conservatively applied over the entire thickness. The capability for leak detection at all plants is required to be at least 1 gpm. However, the actual leak detection capability is much better than this value. The results presented in this report do not consider this factor in determining the leak probability of either axial or circumferential flaws for any potential break size or consequence. In addition, no consideration of plant mitigative action in addressing leaks, such as operator action, was included in the determination of the conditional core damage probabilities.

Critical conclusions from the evaluation are:

- The fabrication history of the weld is a key contributor.
- Changes in inspection frequency or improvements in capability or accuracy have only a small benefit for the locations with the highest leak probabilities.
- Risk results do not justify any required changes in the current 10-year ASME Code Section XI inspection interval, as long as all Alloy 182/82 locations are included.

A review of the critical nozzle leak and risk assessment results would suggest that the reactor pressure vessel outlet nozzle is the most critical when considering potential leaks, plant reliability, and plant safety. The pressurizer surge line, pressurizer spray, decay heat, and pressurizer safety and relief nozzle would follow in order of concern.

The existing analyses and future analyses will be used as inputs into the I&E Guidelines currently under development.

8 CONCLUSIONS

The main conclusion from the butt weld safety assessments is that the risk of leaks is low and the predicted change in core damage frequency is within the requirements of Reg. Guide 1.174. The main contributing factors to this conclusion are as follows:

- Despite there being approximately 1,150 Alloy 82/182 butt welds in domestic PWR plants greater than 1 inch NPS that operate at cold leg temperatures and above, only a few part-depth axial cracks have been detected, only one leak (V.C. Summer) occurred associated with an axial crack that was limited to the width of the V-groove weld, and only one short and shallow circumferential crack has been detected. Including all PWR plants worldwide adds only a small number of part-depth axial cracks and one very small leak (Tsuruga 2).
- Different from the situation prior to 2000 with RPV top head nozzles, most butt welds have been inspected at 10 year intervals per the requirements of the ASME Code Section XI or similar requirements worldwide. These inspections have included volumetric examination of welds 4 inch NPS and larger in diameter unless eliminated as part of a risk based ISI program. The inspection sensitivity has continued to improve over time. The small number of cracks found by these inspections suggests that butt weld PWSCC is not widespread at present. All butt welds examined by UT or by surface examination methods from the outside surface also effectively receive a bare metal visual inspection as part of the NDE process.
- In addition to the nondestructive examinations required by the ASME Code, butt welds are inspected visually for boric acid leaks. The two leaks that have occurred to date (V.C. Summer and Tsuruga 2) were both discovered by visual inspections long before cracks reached critical size or there was any significant boric acid corrosion.
- Finite element stress analyses support the findings in the field that most cracks will be axially oriented. Field experience supports the conclusion that axial cracks will be limited to the width of the Alloy 82/182 weld metal, except for the few cases involving Alloy 600 safe ends) since PWSCC cannot continue into low-alloy steel nozzles or into stainless steel piping on either side of the welds. The fact that the axial cracks arrest before the critical flaw size is reached justifies the use of leakage before risk of rupture even though this case involves an active degradation mechanism.
- In recognition of the importance of visual inspections in detecting leaks at an early stage, the MRP has recommended that all Alloy 82/182 butt weld locations be subjected to a bare metal visual inspection or other equivalent examination, within the next two refueling outages with priority given to inspecting the hot leg and pressurizer nozzle welds during the next outage. See reproduced letter in Appendix B [30]. This recommendation was reinforced under the NEI 03-08 materials initiative and categorized as "needed". Plants that have performed such an inspection during the last refueling need not repeat the inspection.

- Analyses show that 360° part-depth circumferential flaws are unlikely to occur, that the critical length of through-wall circumferential flaws is large, and that for all except one location leak rates of 1 gpm will occur under normal loading conditions significantly before the flaw reaches a critical size even under seismic loading conditions. While the Technical Specification limit is 1 gpm of unidentified leakage, plants are currently working to reduce unidentified leakage to much smaller values.
- Probabilistic fracture mechanics calculations show that the change in core damage frequency due to flaw growth in the 40th year of plant life ranges from 1.85×10^{-8} to 8.74×10^{-8} per year which is within the criteria of 1×10^{-6} specified by Regulatory Guide 1.174.
- While the potential for boric acid corrosion cannot be ruled out, the potential for significant boric acid corrosion is considered to be very low. The low risk is the result of non-destructive examinations to monitor the condition of Alloy 82/182 butt welds in the fleet, visual inspections for boric acid leakage during outages, on-line detection for larger leaks, practical experience with the two butt weld leaks that occurred at V.C. Summer and Tsuruga 2, and practical experience with a large number of leaks from Alloy 600 PWSCC at RPV top and bottom head nozzles, hot leg instrument nozzles, and pressurizer instrument nozzles and heater sleeves.
- The EPRI-MRP is preparing an inspection and examination guideline based on the safety assessment.

9
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A
SUMMARY RESPONSE TO NRC COMMENTS ON REPORT MRP-44, PART 1: ALLOY 82/182 PIPE BUTT WELDS

By letter dated June 14, 2001[2] the NRC provided comments on the industry report MRP-44, Part 1. By letter dated April 22, 2003 [3] the NRC provided additional comments. The following is a summery of the comments in these documents and a summary of the industry response to each comment. References are provided to other sections of this report for supporting details.

Table A-1
General Findings (June 14, 2001 Letter)

NRC Comment	MRP Summary Response
1.1 General Findings – Cracking observed to date has been predominantly axial – Pipe weld axial cracks are bounded by low-alloy or stainless steel at each end – The critical flaw size for axial cracks is several times the weld width – No significant concern exists for boric acid corrosion(1)	The general findings are consistent with the current MRP butt weld safety assessment Further comment regarding the potential for boric acid corrosion is provided in Table A-8
1.2 The above findings provide a basis for continued safe operation while additional analyses and inspections are performed	The conclusion is consistent with the current MRP butt weld safety assessment
1.3 Additional work is necessary to understand the potential for circumferential cracks	The MRP response is provided in Table A-2

(1) This comment was modified by NRC letter dated April 22, 2003 [3]. See Table A-8 for revised comment and response.

Table A-2
Cracking Phenomenon (June 14, 2001 Letter)

NRC Comment	MRP Summary Response
2.1 The potential for circumferential cracking developing at a location where the entire cross section is Alloy 82/182 needs to be addressed	The potential for circumferential cracking has been addressed at several points in the final butt weld safety assessment report. While shallow circumferential cracks may develop in some cases (¶5.6), and part-circumferential through wall circumferential cracks can possibly develop associated with repairs (¶6.4), analyses show that the probability of 360° part-depth circumferential cracks through the Alloy 82/182 weld metal without detection by NDE or leaks from associated axial cracks is extremely low and consistent with the change in core damage frequency specified by Reg. Guide 1.174 (Section 7).
2.2 The following factors should be addressed regarding the predicted cracking – Type of cracks: axial vs. circumferential – Nature of cracks: through-wall vs. 360° part depth, multiple initiation – Stresses: orientations and magnitudes of welding and operating stresses – Repairs: extent and nature – Weld structure: micro and macro – Operating conditions: time and temperature – Crack growth rates	These factors are addressed in the final butt weld safety assessment report – Both axial and circumferential cracks are addressed (¶5.6) – The nature of cracks has been addressed (¶5.6, 6.5) – Stress analyses have been performed of a full range of butt welds from 30" diameter reactor vessel outlet nozzle welds to 1" instrument nozzle welds. The analyses include the effects of welding, weld repairs and operating conditions (¶5.4) – Analyses have been performed to determine the stresses and crack growth for weld repairs ranging from 30° arc length to 360° (¶5.4, 6.4) – The effect of weld structure (dendrites) is incorporated in the crack growth rate models (¶5.2) – The probabilistic analysis incorporates the key parameters of operating time and temperature (Section 7) – A deterministic crack growth rate model has been developed by the MRP with input from an international expert panel (¶5.2)

Table A-3
Visual Inspection for Leaks (June 14, 2001 Letter)

NRC Comment	MRP Summary Response
3.1 The expected leakage levels, considering experience which has shown very low volumes of leakage from tight cracks in combination with the dendritic nature of welds, should be addressed	The butt weld safety assessment addresses leaks from axial and circumferential flaws for a full range of Alloy 82/182 butt weld locations The MRP has recommended that all Alloy 82/182 butt weld locations be subjected to a bare metal visual inspection, or other equivalent examination, within the next two refueling outages with priority given to inspecting the hot leg and pressurizer butt welds during the next outage (¶4.2.1, 8.0). Major conclusions are as follows: – Most through-wall cracks are expected to be axial based on analysis and field experience (¶5.6). The length of axial cracks is limited to the length of the Alloy 82/182 weld except for cases involving butt welds to Alloy 600 instrument nozzles 1" NPS and smaller (¶6.1.4). Leakage from the short axial cracks will be low and detectable only by bare metal visual inspection at early stages. These leaks will pose no risk of significant boric acid corrosion and the cracks will not pose a risk of rupture (¶6.8). The MRP has recommended that insulation be removed from all Alloy 82/182 butt welds within two refueling outages to permit bare metal visual inspections capable of detecting small leaks (¶8.0). – For the case of part-circumferential through-wall circumferential flaws, predictions show that leak rates of 1 gpm will occur for all except one weld prior to reaching critical flaw size (¶6.2, 6.6).
3.2 The ability of current leakage detection systems (inventory makeup, radiation monitoring, sumps, etc.) to detect small volumes of leakage should be addressed	The best method to detect very small amounts of leakage is by bare metal visual inspection (¶4.2.1). The MRP has recommended that plants perform bare metal visual inspections of butt welds during the next two refueling outages (¶4.2.1, 8.0). While plant technical specifications specify a limit of 1 gpm for unidentified leakage, most plants have lowered their criteria for determining the source to leakage of approximately 0.1 gpm (¶ 8.0).
3.3 Plant-specific factors such as insulation or other obstructions that may limit the effectiveness of visual examinations need to be addressed	The MRP has recommended that insulation be removed from all Alloy 82/182 butt welds every refueling outage to permit bare metal visual inspections capable of detecting extremely small leaks (¶4.2.1, 8.0).

Table A-4
ISI Capability (June 14, 2001 Letter)

NRC Comment	MRP Summary Response
4.1 Presently required ISI examinations need to be augmented. UT examinations do not appear to be effective in detecting all cases of PWSCC. Specifically, UT missed cracks at V.C. Summer during 10-year ISI program that were detected by leakage	The current status of NDE for dissimilar metal butt welds is reviewed (¶4.2). The review has demonstrated that NDE inspection capability has improved over the years and is still improving (¶4.2.4, 4.2.5). Uncertainties in NDE capability reinforce the need for visual inspections to ensure that any leaks which do occur are detected at an early stage (¶4.2.1, 8.0)
4.2 The report concludes an absence of widespread problems based on ISI inspections. Is it possible that the absence of problems is really just a reflection of poor inspectability by UT?	While this is a possibility, it is considered unlikely. The main reason is that if large numbers of cracks initiate and they propagate rapidly, then a large number of small leaks would be expected. To date, the large number of visual inspections worldwide has shown only two leaks (¶4.2, 4.3). Similarly, NDE performed in other countries has confirmed the domestic experience of few reportable indications (¶4.3).
4.3 Inspection improvements are necessary – Use the best available techniques – Address known concerns such as the effect of ID surface conditions – Include real PWSCC cracks in NDE qualification mockups	Significant effort has been performed and is still ongoing to improve nondestructive inspection capability. Much of this work is being accomplished through the EPRI NDE Center (¶4.2.4).

Table A-5
Fracture Assessment and Leak-Before-Break (June 14, 2001 Letter)

NRC Comment	MRP Summary Response
5.1 The staff agrees that axial cracks are not a safety concern	Comment is consistent with MRP-44, Part 1
5.2 MRP-44 does not adequately substantiate that large part-depth 360° flaws may not develop in service. Analyses need to show that large part-depth circumferential flaws cannot develop, and analyses must consider effects such as multiple flaw initiation	Part-depth 360° flaws have not been experienced to date in PWR plants (¶5.6.1) and information provided by General Electric suggests that such cracks only occurred in a unique situation in a single BWR plant (¶5.6.2). These findings are consistent with finite element and fracture mechanics analyses (¶5.6.3, 6.4, and 6.5).
5.3 More detail is needed regarding leakage calculations. For example, calculations should consider the crack surface roughness, number of 45° and 45° turns, uncertainties, etc. Further, the licensing basis calculations for approving LBB for piping systems include a factor of 10 on leakage	Details regarding the leak rate models are provided in the Westinghouse and AREVA deterministic analyses (¶6.6).
5.4 More detail is required regarding the critical flaw size, including assumed material properties and loadings	Details regarding the fracture assessment are provided in the Westinghouse, AREVA, and Structural Integrity Associates deterministic analyses (¶6.1 through 6.4).

Table A-6
Weld Residual Stress Assessment (June 14, 2001 Letter)

NRC Comment	MRP Summary Response
6.1 Analyses in Appendix C were useful in understanding specific issues associated with VC Summer and foreign experience	No response necessary
6.2 Several items of interest were not included in Appendix C – Through-wall thickness profiles showing welding/repair residual stresses and superimposed operating condition stresses – Investigation into the adequacy of axi-symmetric modeling and elastic-perfectly plastic material properties – Details of ANSYS thermal and residual stress analysis models such as mesh refinement studies, and a description of how properties of previous weld passes were changed during re-melting and solidification due to new passes being deposited	Finite element work has been completed that addresses these issues (¶5.4).
6.3 Work should be expanded to cover a full range of designs and fabrications, including outliers to provide a more balanced assessment of stresses	A survey was performed to identify the full range of dissimilar metal Alloy 82/182 butt welds in the three NSSS plant designs (¶3.1, 3.2, 3.3). The finite element stress analysis report includes a full range of typical nozzles including RPV inlet/outlet nozzles, pressurizer surge nozzles, pressurizer safety relief nozzles, pressurizer instrument nozzles and high pressure injection nozzles (¶5.4). These nozzles cover diameters ranging from about 1" to 30". Repairs modeled include 360° repairs to the inside surface and 30°, 60° and 90° partial arc repairs to the inside surface for nozzles where inside surface repairs are possible from an access standpoint. Analyses were also performed for partial-arc weld repairs from the outside surface (¶5.5).

Table A-7
Risk Assessment (June 14, 2001 Letter)

NRC Comment	MRP Summary Response
7.1 Appendix A, Section 7, "Risk Assessment" concludes that risk of core damage due to PWSCC related large leaks is expected to remain insignificant, and that a number of potential actions are available to reduce uncertainty and manage PWSCC degradation	No response necessary
7.2 Staff requests that further technical justification for the core damage risk assessment be provided based on realistic initiating event frequencies, and bounded by technically justified uncertainty bands for all three types of NSSS designs	A probabilistic risk assessment has been performed that incorporates all of the issues noted (¶7).
7.3 Risk-informed assessments should provide sufficient details that the staff can verify risk-informed results	The probabilistic analysis is summarized in Section 7 of this summary report and complete details are provided in the vendors analysis report and accompanying references.

Table A-8
Boric Acid Corrosion (April 22, 2003 Letter)

NRC Comment	MRP Summary Response
The conclusion in the initial June 14, 2001 letter from the NRC stating that "No significant concern exists for boric acid corrosion." was revised by letter dated April 22, 2003 to indicate that experience at Davis-Besse showed that significant damage could occur due to boric acid corrosion resulting from leaks from PWSCC cracks that are less than currently detectable by on-line means.	The subject of boric acid corrosion is addressed in the current report (¶6.8). The potential for boric acid corrosion, and the uncertainties in NDE capability to detect cracks at an early stage, are the basis for the industry recommendation for all plants to perform bare metal visual inspections of all butt welds over the next two refueling outages with priority to the pressurizer and hot leg locations during the next refueling outage (¶4.2.1, 8.0). Longer term inspection recommendations are being prepared by the EPRI-MRP.

B
MRP LETTER 2003-039 TO ALL OPERATING PWR PLANTS, “RECOMMENDATION FOR INSPECTION OF ALLOY 600/82/182 PRESSURE BOUNDARY COMPONENTS,” DATED JANUARY 20, 2004

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January 20, 2004

MRP 2003-039

Subject: Recommendation for Inspection of Alloy 600/82/182 Pressure Boundary Components

During recent years, there have been a number of leaks in the PWR primary system pressure boundary due to cracks in Alloy 600/82/182 components and welds. Examples include the hot leg nozzle weld at V. C. Summer, a steam generator bowl drain line at Catawba, the top-of-pressurizer safety/relief valve nozzle welds at Palisades and Tsuruga, the bottom mounted instrument nozzles (BMIs) at South Texas Project Unit 1, numerous small bore lines in the CE fleet, and numerous vessel head penetrations. In addition, some cracks or indications have been discovered by volumetric and/or surface NDE before growing through-wall. These include cracks in Ringhals 3 & 4 hot leg nozzle welds, the Tihange surge line nozzle weld, V. C. Summer hot and cold leg nozzle welds, and numerous vessel head penetrations. With the exception of the BMIs (currently being analyzed), breaks or leaks associated with PWSCC of Alloy 600/182/82 are typically analyzed and bounded by a plant's design basis accident analyses. A significant line break at one plant would, however, represent an economic concern for the entire US PWR fleet. Because Alloy 600/82/182 is used as a transition material between low alloy steel and stainless steel, leakage from these locations represents a threat to the associated carbon steel material through boric acid corrosion degradation. Such leakage at Davis-Besse resulted in the most significant wastage to date of the carbon steel reactor vessel pressure boundary.

Most of the through-wall cracks have been discovered by evidence of leakage (boric acid residue), but in many cases this evidence has not manifested itself outside the insulation. Additionally, in the steam space, the extent of boric acid residue is limited, and evidence of leakage may only manifest itself in a visible spray pattern or rust streaks. Visual examination of borated systems is often the best way to detect leaks, but if the leak rate is very low, as has been the case for a number of the tight PWSCC cracks, examination of the component without removal of the insulation has been shown to be ineffective. Also, some boric acid deposits have been identified that appear to have been associated with leaks that may have been active for several years prior to discovery. This period is significantly longer than the 4-hour hold required by the ASME B&PV Code to inspect insulation for evidence of leakage during pressure tests, which is additional evidence that the Code inspection may not be fully adequate to detect PWSCC leakage from these components and welds.

Each plant will ultimately need to develop a planned inspection program for Alloy 600/82/182 taking into account the relative likelihood of leakage and the safety and economic risk of leakage. In the long term, these plans should be based on the industry recommended programs resulting from ongoing safety assessments and the plant's own assessments of safety and economic risks. The Butt Weld Working Group of the Alloy 600 Issues Task Group is finalizing safety assessments for Alloy 82/182 butt welds and is considering some form of augmented volumetric inspection recommendations, over and above the normal ASME B&PV Code or Risk Informed ISI required inspections. The need for such augmented volumetric inspection is driven by the PWSCC crack growth rate in these weld metals and the desire to prevent or minimize leakage events discovered by visual inspections. **In the interim, until those recommendations are finalized, the MRP recommends that a direct visual inspection of the bare metal (either through removal of insulation or remote visual examination inside the insulation) or equivalent alternative examination be performed at**

all Alloy 600/182/82 pressure boundary locations normally operated at greater than or equal to 350°F in the primary system within the next 2 refueling outages at each plant, unless performed during your most recent refueling outage.

For Alloy 600/82/182 locations in water space, visually inspect for evidence of leakage as much of the circumference and the surrounding areas as reasonably achievable. For Alloy 600/82/182 locations in steam space, this inspection should be essentially 100% of the surface because of the limited deposits that may be present.

For plants that have already developed comprehensive inspection programs, the program should evaluate operating experience, as it becomes available, to ensure the bases for inspection type and frequency remain valid.

In planning upcoming outages, priority should be given to the hottest locations (such as the pressurizer and hot leg weld locations) during the next refueling outage. Plants whose design significantly impedes access to perform the recommended examinations should initiate expedited actions, up to and including physical modifications, to allow implementation of the recommendation at the earliest possible scheduled outage opportunity. These recommendations are not intended to modify inspection programs for upper heads per the NRC Order EA-03-009, or the recent MRP recommendation for bare metal visual inspections of bottom mounted instruments (Ref. MRP 2003-17). Alternatives to the recommendations contained in this letter should be documented at the individual plant sites and be reflective of recent operating experience.

While implementation of these recommendations does not relieve any plant of their obligations to implement volumetric examinations in accordance with the ASME B&PV Code, Appendix VIII[1], and NRC regulations, it will ensure early detection of any existing leaks and will provide the utility and the industry an assessment of the condition of the plants.

In light of leakage and cracking events discussed earlier in this letter, non-visual NDE may ultimately be a prudent and necessary component in a comprehensive inspection plan to fully evaluate the condition of the Alloy 600/82/182 materials in the primary loop, particularly following visual detection of a leak.

Leslie N Hartz
Chair, MRP Senior Representatives
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[1] These bare metal examinations can also enable the gathering of useful plant-specific information on joint configurations and access to prepare for future volumetric examinations. This is because weld geometric and access conditions present at some locations may limit the applicability of existing qualified UT procedures. In particular, existing dissimilar metal weld qualifications to ASME Section XI, Appendix VIII, Supplement 10 have limitations on detection or sizing that depend upon joint contour, crown condition, tapers, etc. Some of the critical locations for PWSCC susceptibility are at high temperature locations (e.g. pressurizer spray, relief, and surge lines) that may have to be examined manually, which also has limitations with respect to existing qualified procedures. Thus, it will also be important to determine which welds can be inspected with automated versus manual techniques. Finally, since some as-built configurations are not covered in the PDI DM qualifications set, some sites may need to develop site-specific mockups. Availability of the above information will enable licensees to adequately prepare for future volumetric examinations.